Index Properties

1. Phase Relationships
2. Soil Texture
3. Grain Size and Grain Size Distribution
4. Particle Shape
5. Atterberg Limits
6. Indices

What is Soil?

Three phase system

- Solid
- Water
- Air

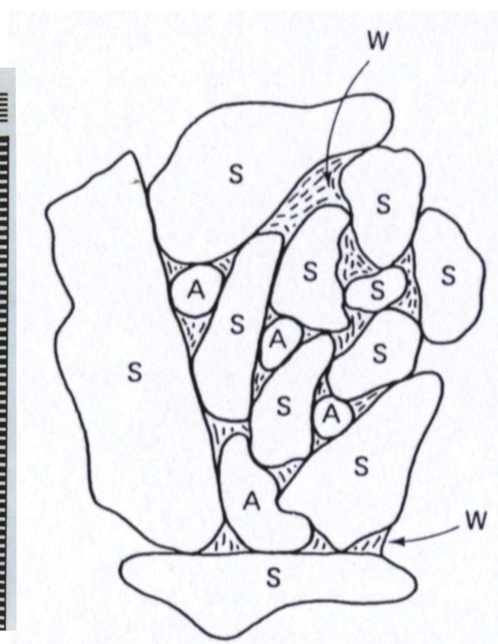
1. Phase Relations

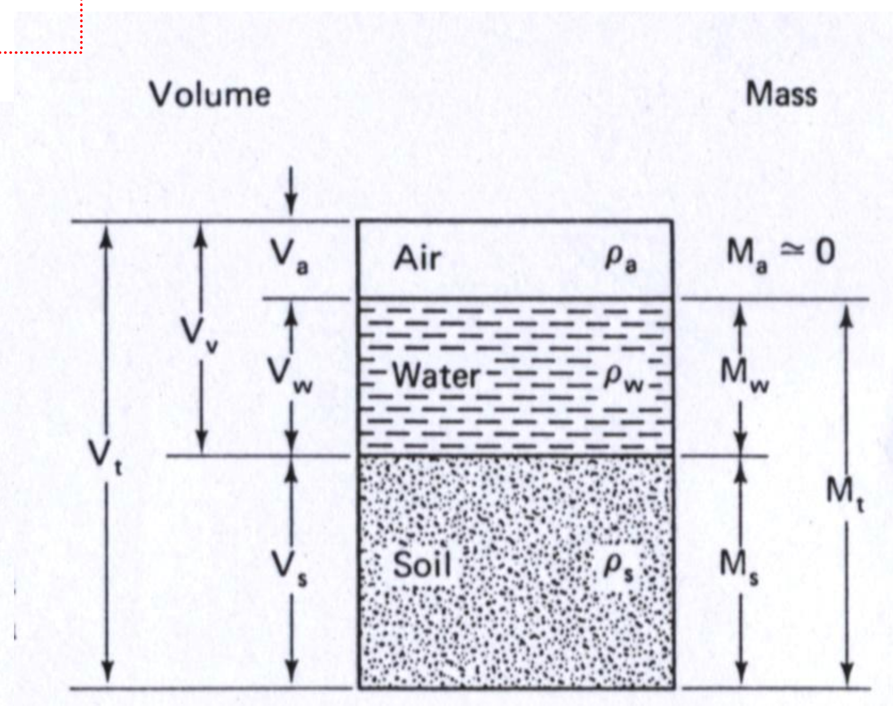
Three Phases in Soils

S : Solid — Soil particle

W: Liquid — Water (electrolytes)

A: Air — Air





Objectives

To compute the masses (or weights) and volumes of the three different phases.

Notation

M = mass or weight

V = volume

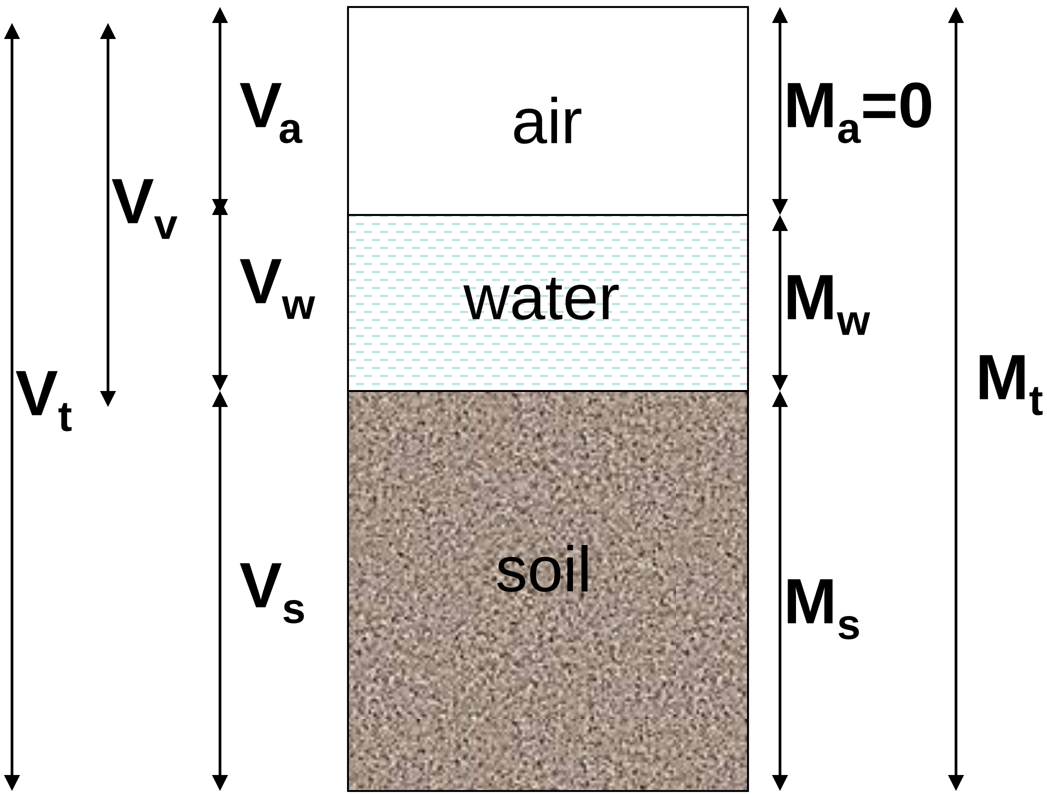
s = soil grains

w = water

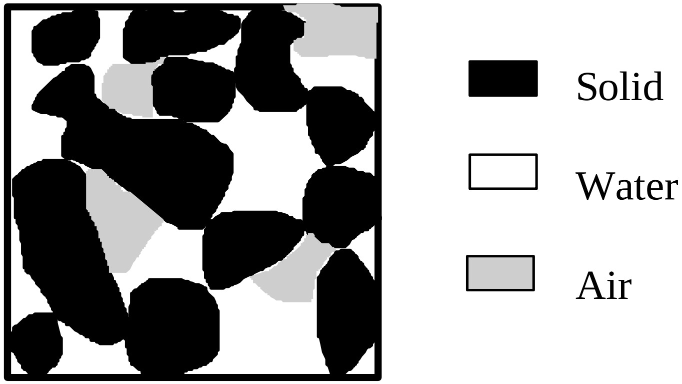
a = air

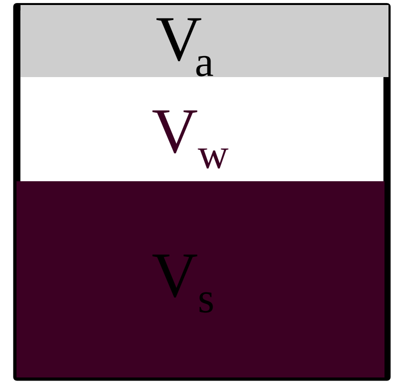
v = voids

t = total



Phase Diagram





- Soil is generally a three phase material
- Contains solid particles and voids
- Voids can contain liquid and gas phases

Phase	Volume	Mass	Weight
Air	V_a	0	0
Water	V_w	M_w	W_w
Solid	V_s	M_s	W_s

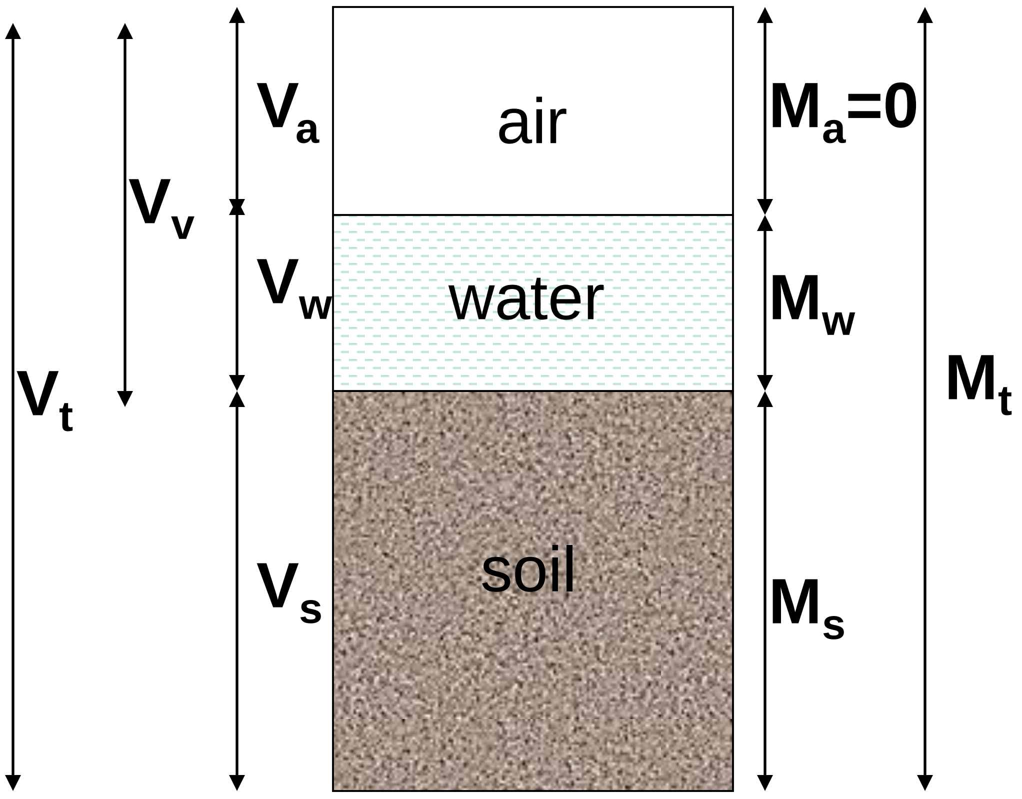
Definitions

Water content (w) is a measure of the water present in the soil.

$$w = \frac{M_W}{M_S} \text{ X } 100\%$$

Expressed as percentage.

Range = 0 – 100+%.



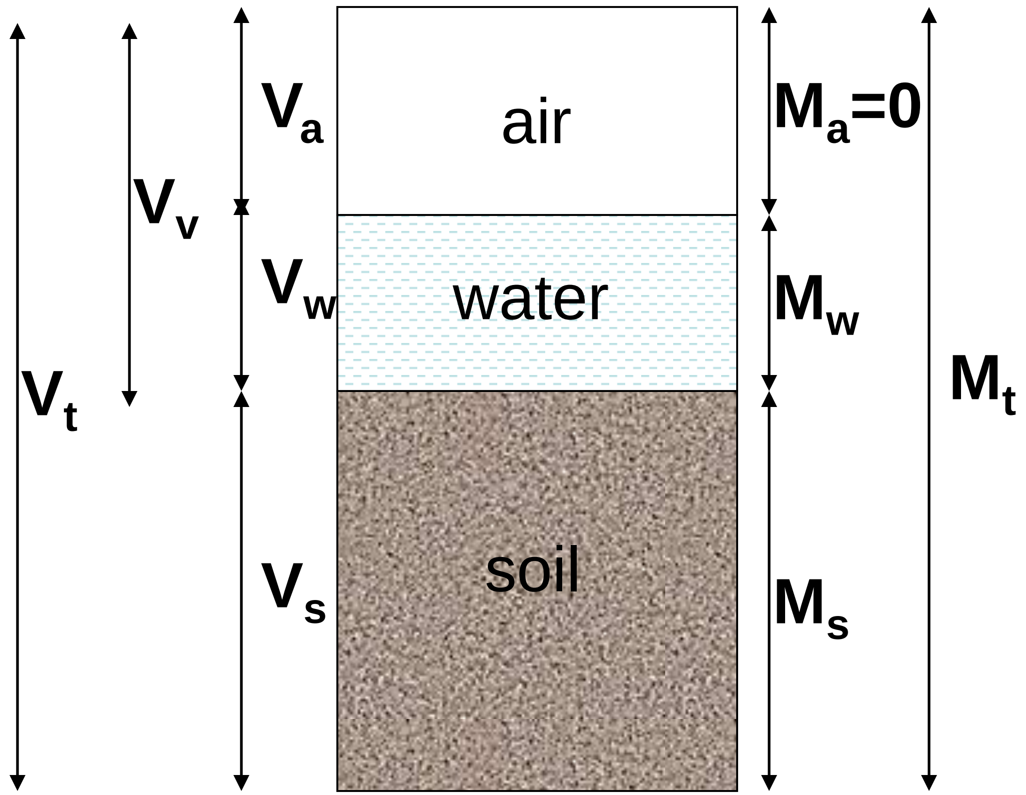
Phase Diagram

Definitions

Void ratio (e) is a measure of the void volume.

$$e = \frac{V_V}{V_S}$$

Expressed in decimals



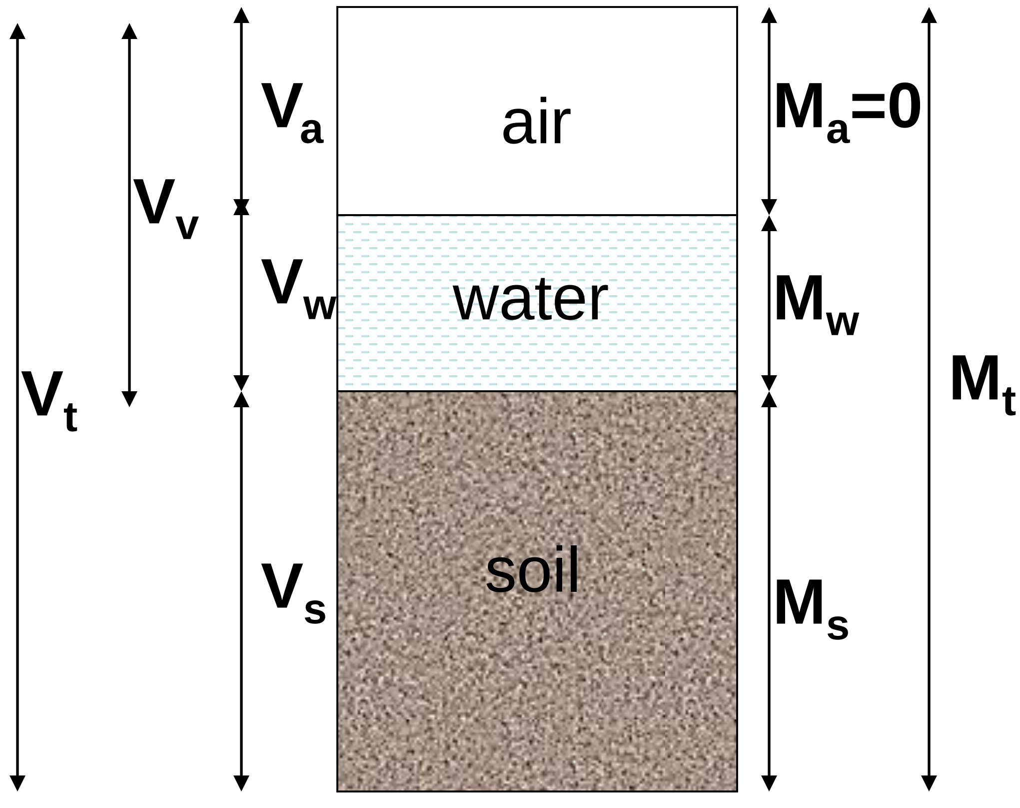
Phase Diagram

Definitions

Porosity (n) is also a measure of the void volume, expressed as a percentage.

$$n = \frac{V_V}{V_T} \text{ X } 100\%$$

Theoretical range: 0 – 100%



Phase Diagram

The voids ratio is defined as

$$e = \frac{V_v}{V_s}$$

and the porosity as

$$n = \frac{V_v}{V}$$

The relation between these quantities can be simply determined as follows

$$V_s = V - V_v = (1 - n) V$$

Hence

$$e = \frac{V_v}{V_s} = \frac{V_v}{(1 - n) V} = \frac{n}{1 - n}$$

Definitions

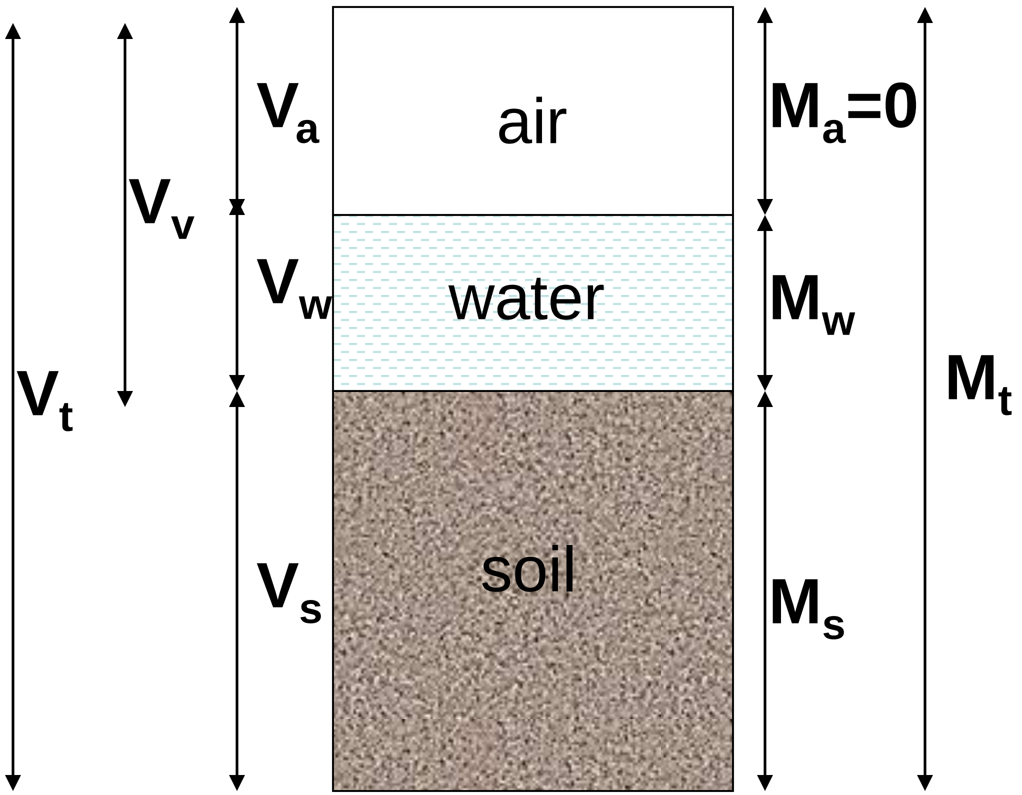
Degree of saturation (S_r) is the percentage of the void volume filled by water.

$$S_r = \frac{V_w}{V_v} \times 100\%$$

Range: 0 – 100%

Dry

Saturated



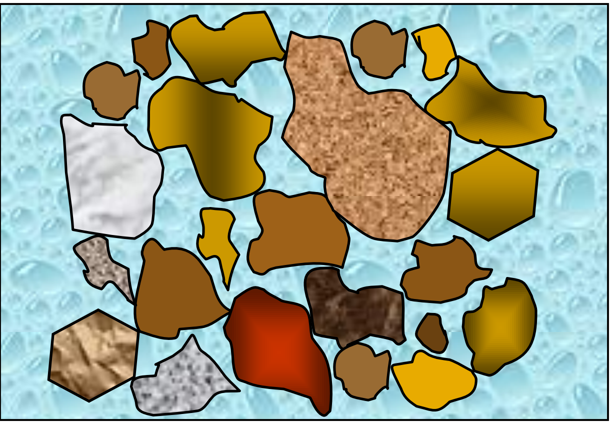
Phase Diagram

Soil at Different Moisture Levels/ Degree of Saturation:

At 100 % Saturation

(Saturated Soil)

S_r=1

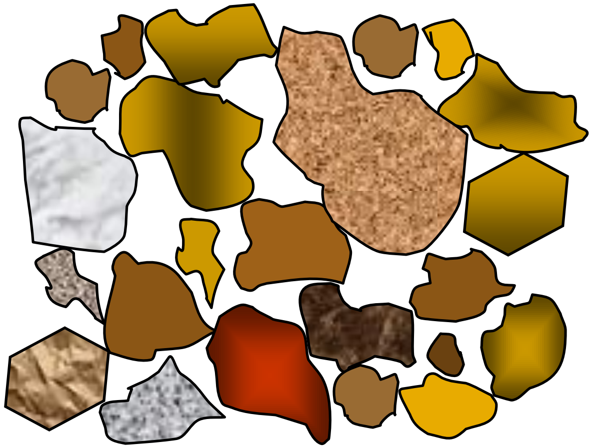


Pore spaces are completely filled with water

At 0 % Saturation

(Dry Soil)

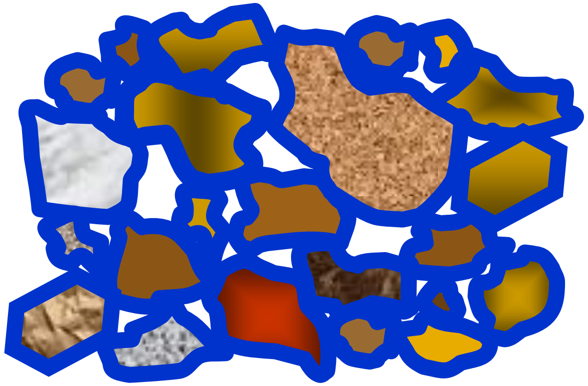
S_r=0



Pore spaces are completely filled with air

(Partially Saturated Soil)

S_r <1 but >0



Pore spaces are partially filled with water

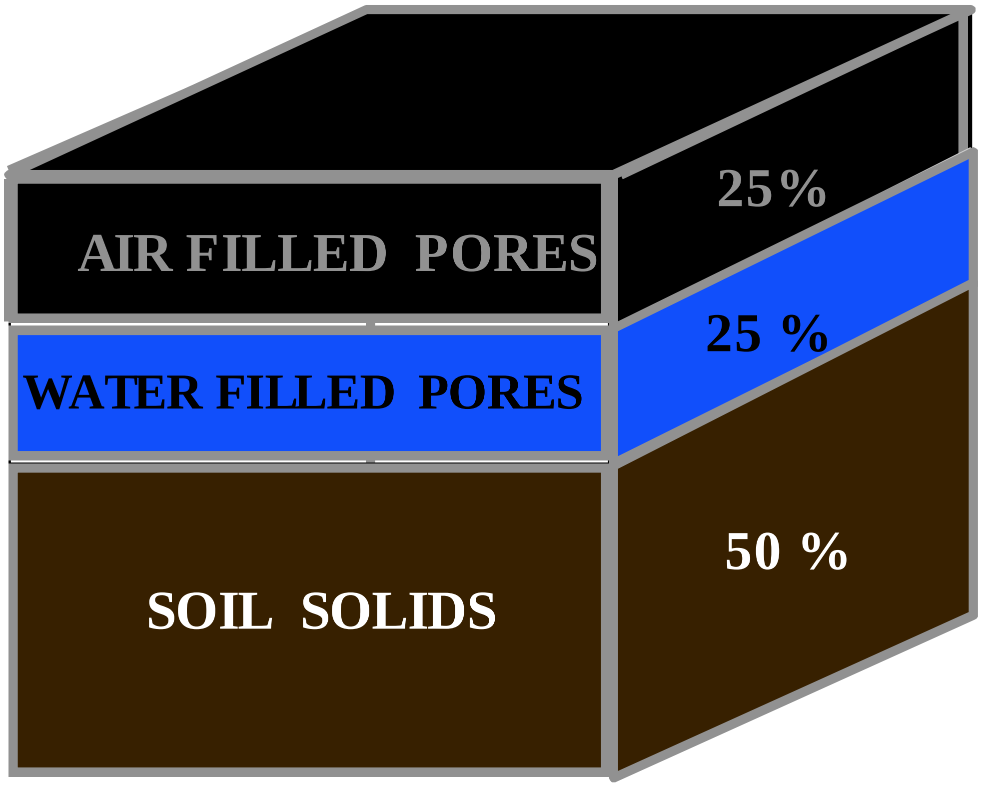
Degree of Saturation of Sand

Condition of sand	Degree of Saturation(%)
Dry	0
Humid	1 - 25
Damp	26 - 50
Moist	51 - 75
Wet	76 - 99
Saturated	100

A Simple Example

SOIL COMPONENTS

idealized soil



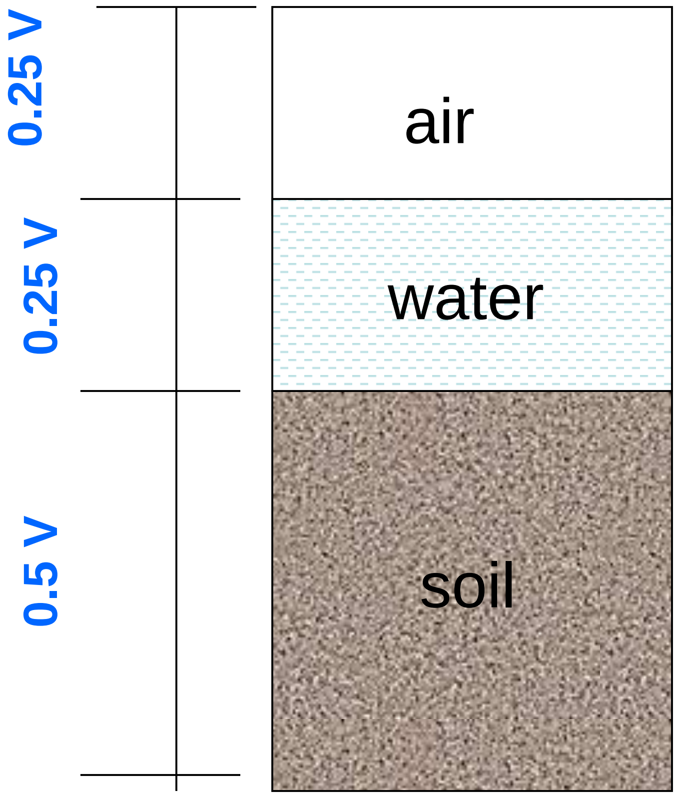
A Simple Example

In this illustration,

$e = 1$

$n = 50\%$

$S_r = 50\%$

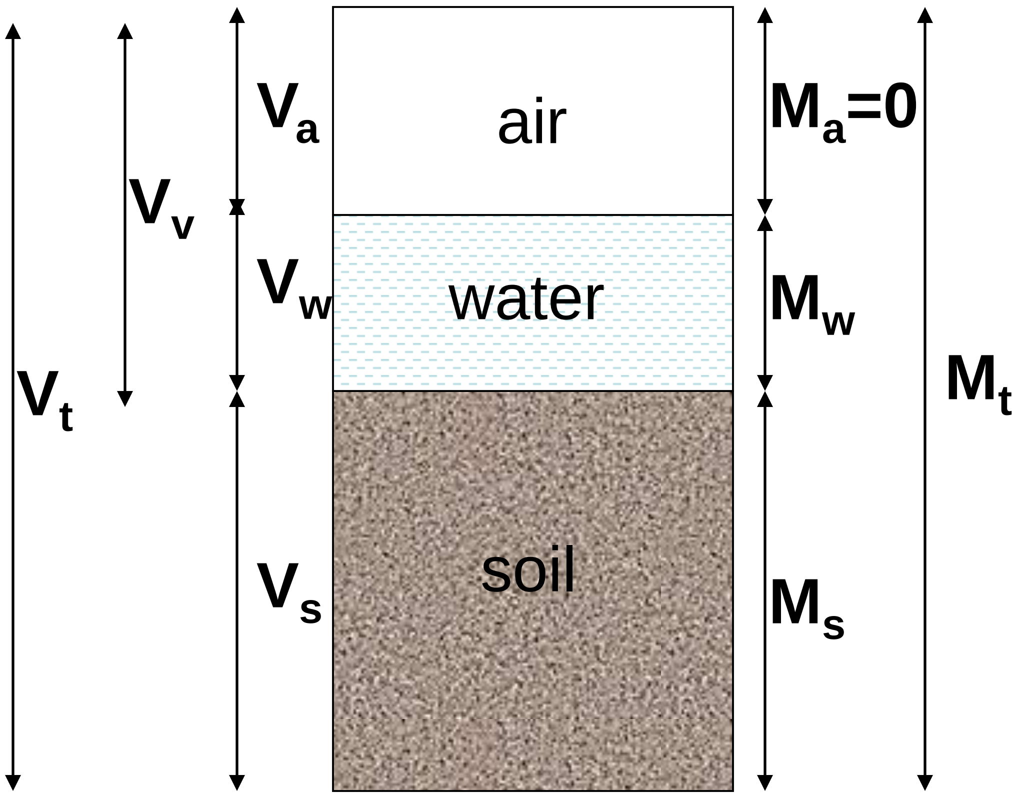


Definitions

Bulk density (ρ_m) is the density of the soil in the current state.

$$\rho_m = \frac{M_T}{V_T}$$

Units: t/m^3, g/ml, kg/m^3



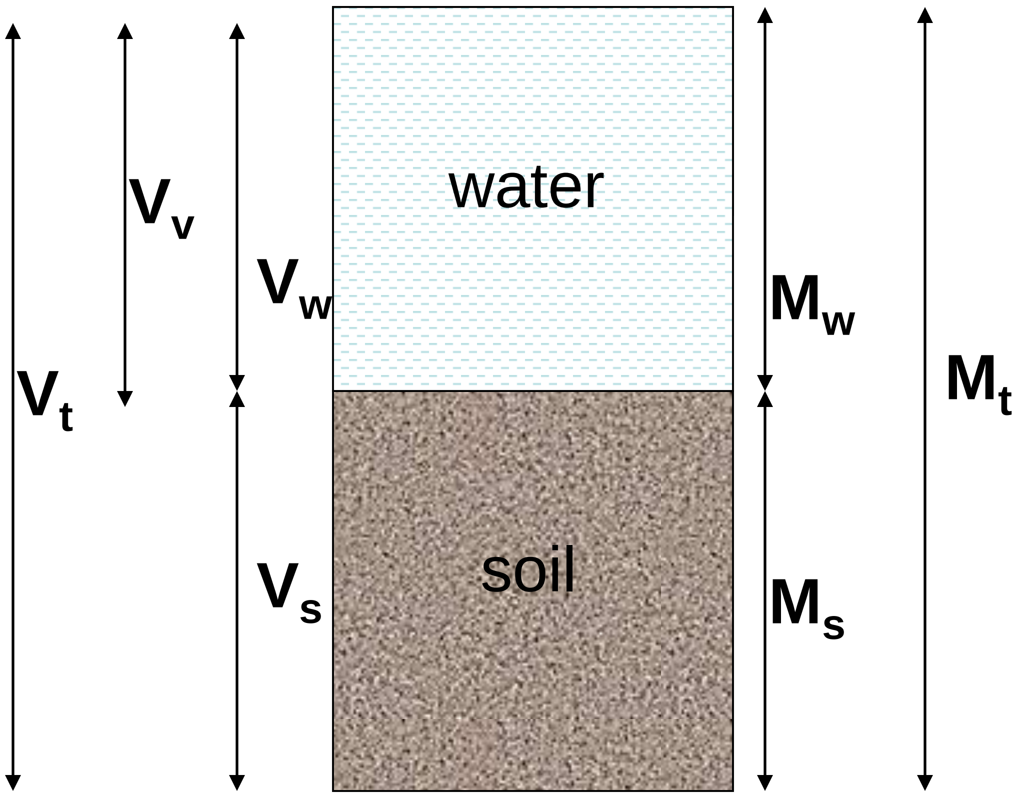
Phase Diagram

Definitions

Saturated density (ρ_{sat}) is the density of the soil when the voids are filled with water.

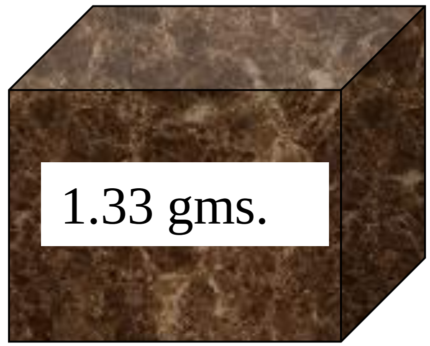
$$\rho_{sat} = \frac{M_T}{V_T}$$

Where we can find saturated soils???



Bulk Density: a measure of soil compaction

Sample is made of Solids and Pore Spaces



1 cm. (so, there is 1 cubic centimeter of soil)

To calculate Bulk Density:

Volume = 1 cm^3

Weight = 1.33 gms

$$\text{Bulk Density} = \frac{\text{Weight of Soil}}{\text{Volume of Soil}}$$

$$\text{Bulk Density} = \frac{1.33}{1}$$

$$\text{Bulk Density} = 1.33 \text{ gms} / cm^3$$

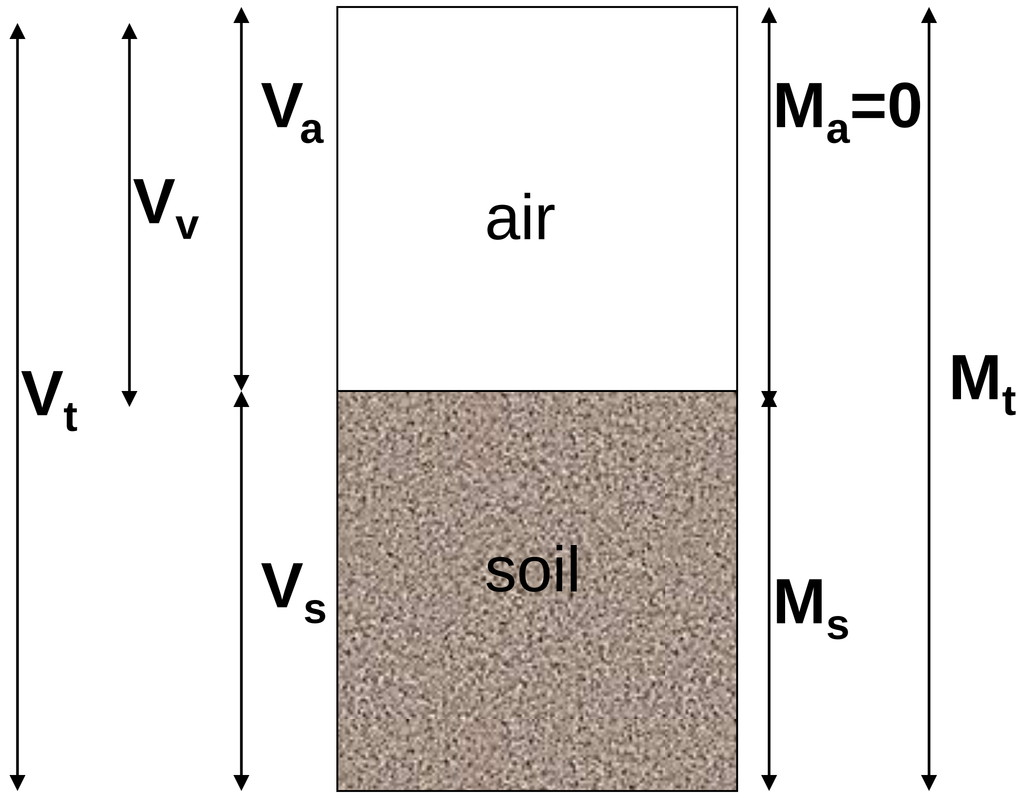
Definitions

Dry density (ρ_d) is the density of the soil in dry state.

$$\rho_d = \frac{M_S}{V_T}$$

Units: t/m^3, g/ml, kg/m^3

Where we can find dry soils????



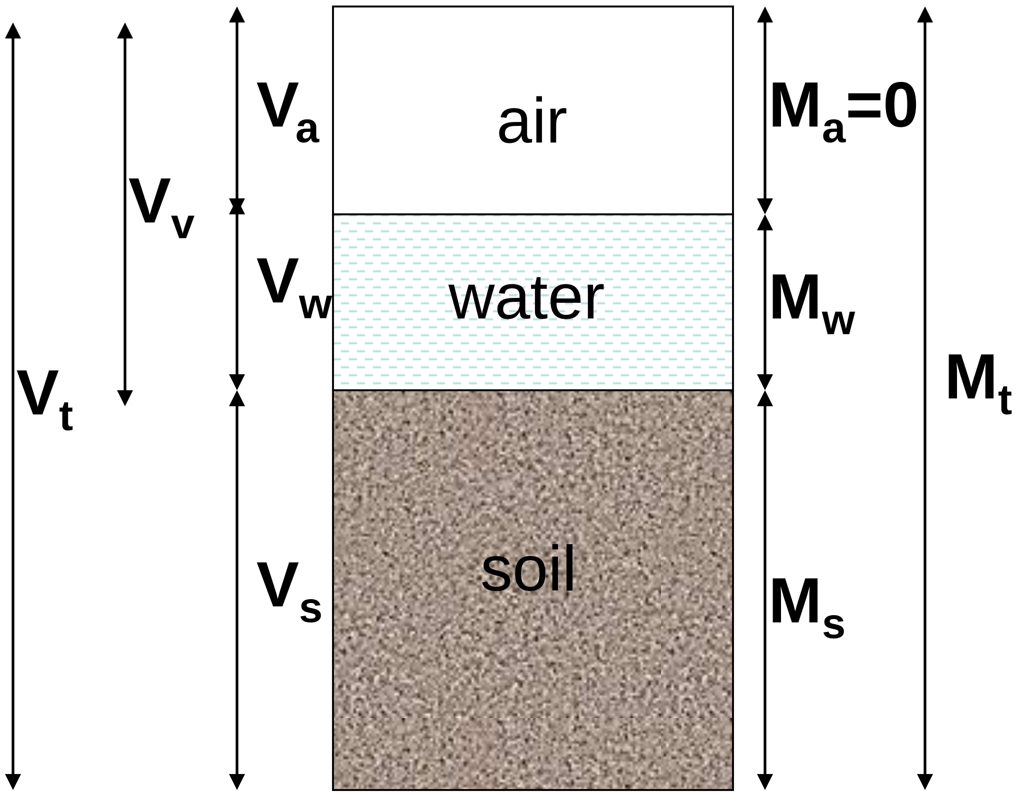
Phase Diagram

Definitions

Density of Solids (ρ_s) is the density of the soil solids in soil .

$$\rho_s = \frac{M_s}{V_s}$$

Units: t/m^3, g/ml, kg/m^3



Phase Diagram

Definitions

Submerged density (ρ') is the effective density of the soil when it is submerged.

$$\rho' = \rho_{sat} - \rho_w$$

Specific Gravity

This is defined by

$$G = \frac{Density\ of\ Material}{Density\ of\ Water} = \frac{\rho}{\rho_w}$$

$$G = \frac{Unit\ Weight\ of\ Material}{Unit\ Weight\ of\ Water} = \frac{\gamma}{\gamma_w}$$

- $G_s \cong 2.65$ for most soils
- G_s is useful because it enables the volume of solid particles to be calculated from mass or weight

$$V_s = \frac{M_s}{\rho_s} = \frac{M_s}{G_s\ \rho_w} = \frac{W_s}{\gamma_s} = \frac{W_s}{G_s\ \gamma_w}$$

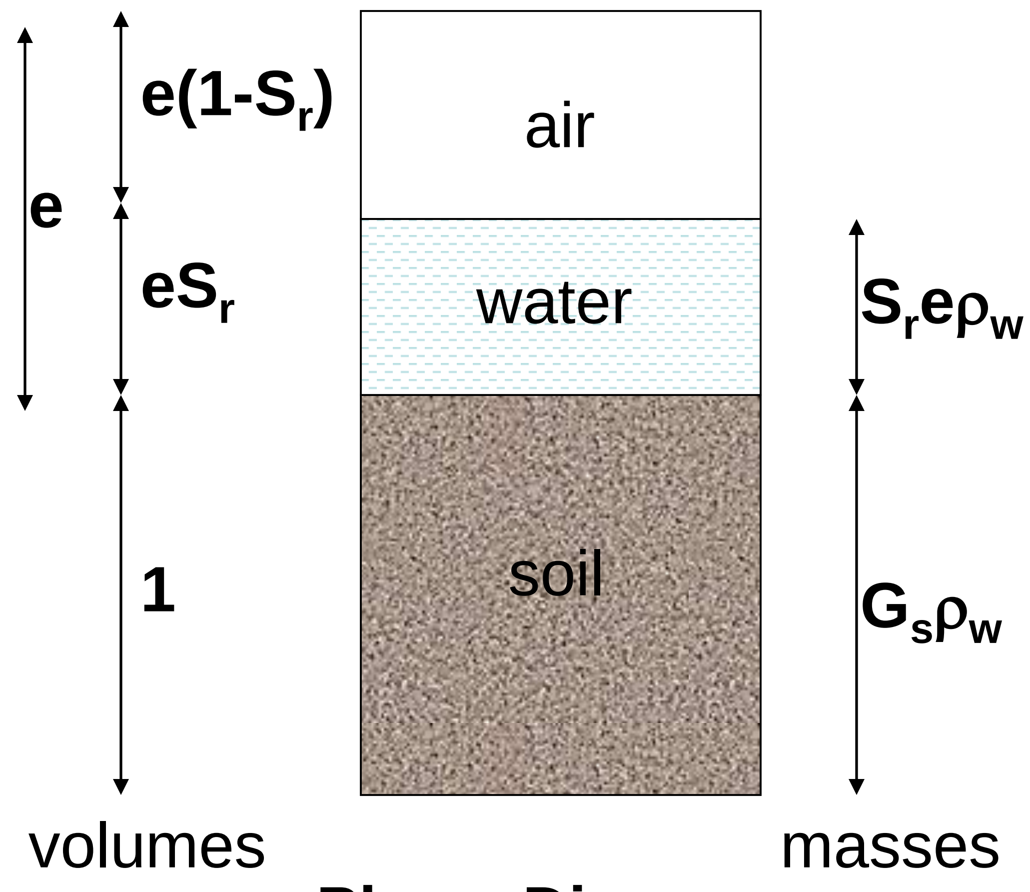
Phase Relations

Consider a fraction of the soil where $\mathbf{V_s = 1}$.

The other volumes can be obtained from the previous definitions.

The masses can be obtained from:

Mass = Density x Volume



Phase Diagram

- The phase volumes may now be expressed in terms of e, S_r, G_s, γ and V_s
- $V_w = e S_r V_s$ $V_a = V_v - V_w = e V_s (1 - S_r)$

Assuming $V_s = 1\ m^3$, the following table can be produced

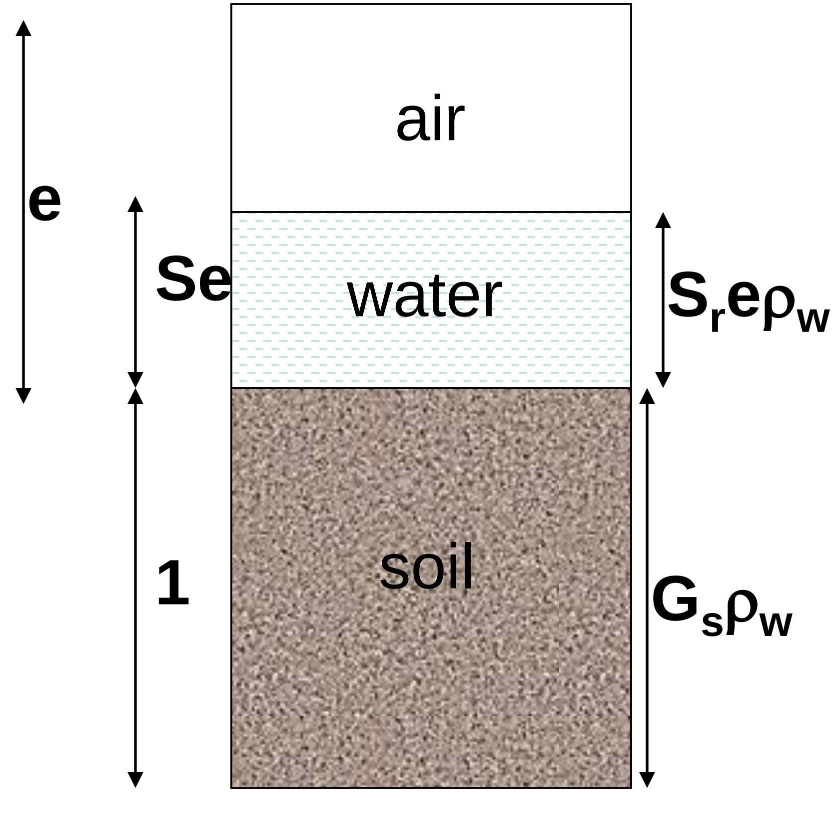
Phase	Volume	Mass	Weight
Air	$e (1 - S_r)$	0	0
Water	$e S_r$	$e S_r \rho_w$	$e S_r \gamma_w$
Solid	1	$G_s \rho_w$	$G_s \gamma_w$

Phase Relations

From the previous definitions,

$$w = \frac{M_W}{M_S} = \frac{Se}{G_S}$$

$$n = \frac{V_V}{V_T} = \frac{e}{1+e}$$



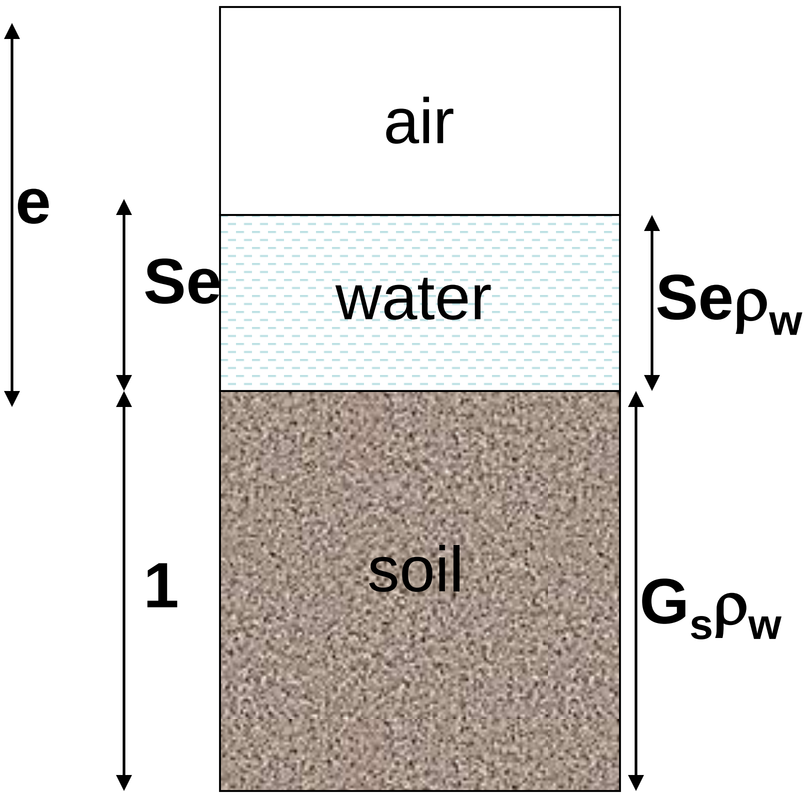
Phase Diagram

Phase Relations

$$\rho_m = \frac{M_T}{V_T} = \frac{G_S + Se}{1+e}\rho_W$$

$$\rho_{sat} = \frac{M_T}{V_T} = \frac{G_S + e}{1+e}\rho_W$$

$$\rho_d = \frac{M_S}{V_T} = \frac{G_S}{1+e}\rho_W$$



Phase Diagram

Key Points

- Try not to *memorize* the equations. ***Understand*** the definitions, and develop the relations from the phase diagram with $V_S = 1$;

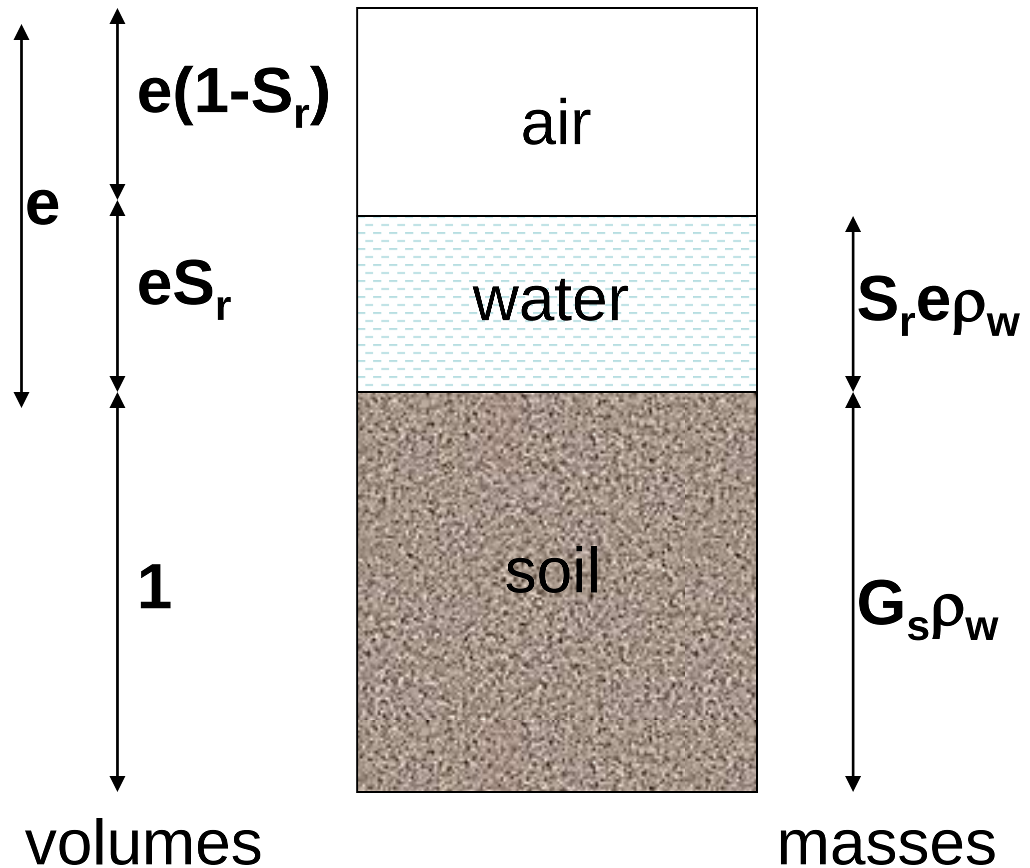
- Assume G_S (2.6-2.8) when not given;

- Do not mix densities and unit weights;

- Soil grains are incompressible. Their mass and volume remain the same at any void ratio.

A Suggestion..

If you can remember one thing in phase relations, that should be ..



Phase Diagram

Table 3.1 Various Forms of Relationships for γ, γ_d, and γ_{sat}

Moist unit weight (γ)		Dry unit weight (γ_d)		Saturated unit weight (γ_{sat})	
Given	**Relationship**	**Given**	**Relationship**	**Given**	**Relationship**
w, G_s, e	$\dfrac{(1+w)G_s\gamma_w}{1+e}$	γ, w	$\dfrac{\gamma}{1+w}$	G_s, e	$\dfrac{(G_s+e)\gamma_w}{1+e}$
S, G_s, e	$\dfrac{(G_s+Se)\gamma_w}{1+e}$	G_s, e	$\dfrac{G_s\gamma_w}{1+e}$	G_s, n	$[(1-n)G_s+n]\gamma_w$
w, G_s, S	$\dfrac{(1+w)G_s\gamma_w}{1+\dfrac{wG_s}{S}}$	G_s, n	$G_s\gamma_w(1-n)$	G_s, w_{sat}	$\left(\dfrac{1+w_{sat}}{1+w_{sat}G_s}\right)G_s\gamma_w$
w, G_s, n	$G_s\gamma_w(1-n)(1+w)$	G_s, w, S	$\dfrac{G_s\gamma_w}{1+\left(\dfrac{wG_s}{S}\right)}$	e, w_{sat}	$\left(\dfrac{e}{w_{sat}}\right)\left(\dfrac{1+w_{sat}}{1+e}\right)\gamma_w$
S, G_s, n	$G_s\gamma_w(1-n)+nS\gamma_w$	e, w, S	$\dfrac{eS\gamma_w}{(1+e)w}$	n, w_{sat}	$n\left(\dfrac{1+w_{sat}}{w_{sat}}\right)\gamma_w$
		γ_{sat}, e	$\gamma_{sat}-\dfrac{e\gamma_w}{1+e}$	γ_d, e	$\gamma_d+\left(\dfrac{e}{1+e}\right)\gamma_w$
		γ_{sat}, n	$\gamma_{sat}-n\gamma_w$	γ_d, n	$\gamma_d+n\gamma_w$
		γ_{sat}, G_s	$\dfrac{(\gamma_{sat}-\gamma_w)G_s}{(G_s-1)}$	γ_d, S	$\left(1-\dfrac{1}{G_s}\right)\gamma_d+\gamma_w$
				γ_d, w_{sat}	$\gamma_d(1+w_{sat})$

2. Soil Texture

Soil Texture:

- The way the soil "feels" is called the soil texture.
- Soil texture depends on the amount of each size of mineral particles in the soil.
- Sand, silt, and clay are names that describe the size of individual mineral particles in the soil.
  - ➔ **Sand** are the largest particles and they fell "gritty"
  - ➔ **Silt** are medium sized, and they feel soft, silky or "floury"
  - ➔ **Clay** are the smallest sized particles, and they feel "sticky"

3. Grain Size and Grain Size Distribution

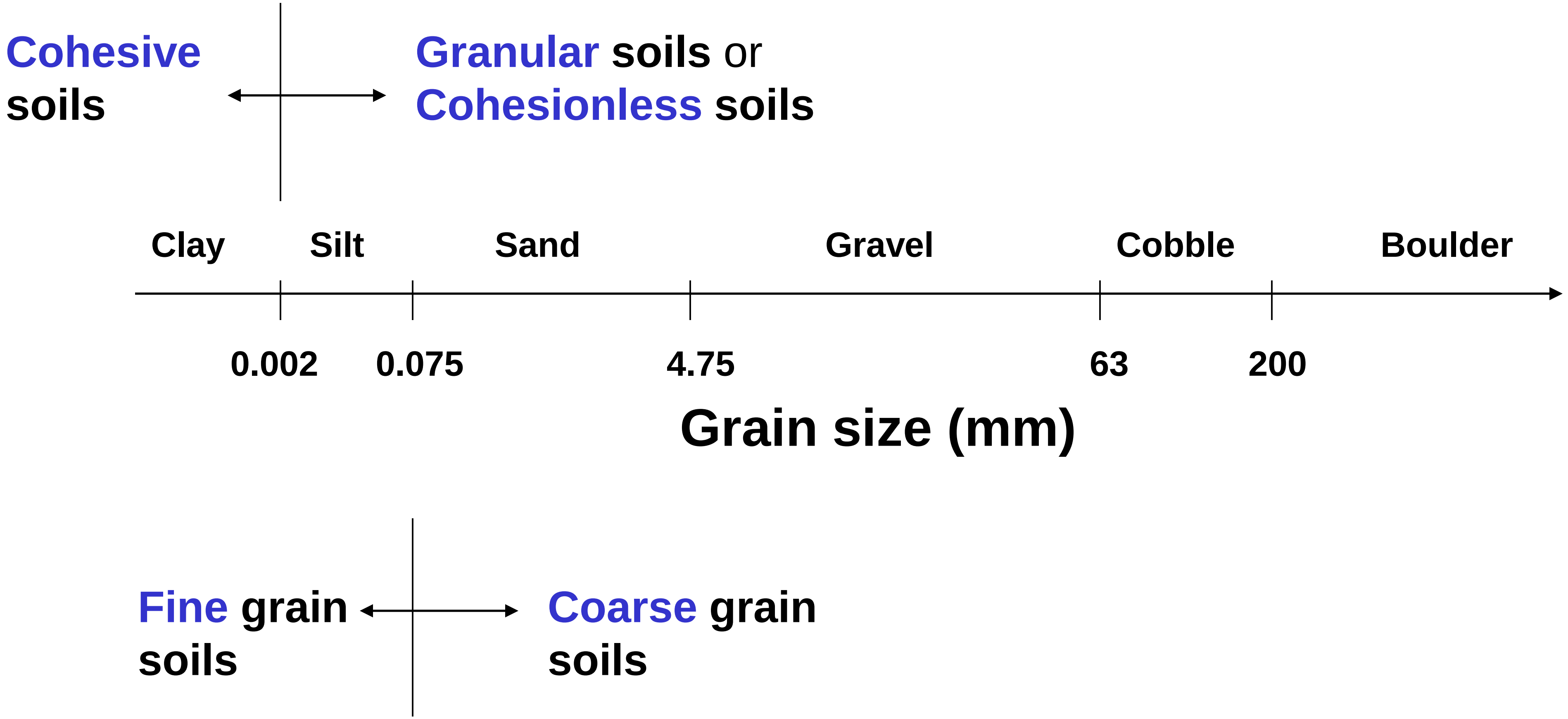
Purposes of Grain Size Analysis

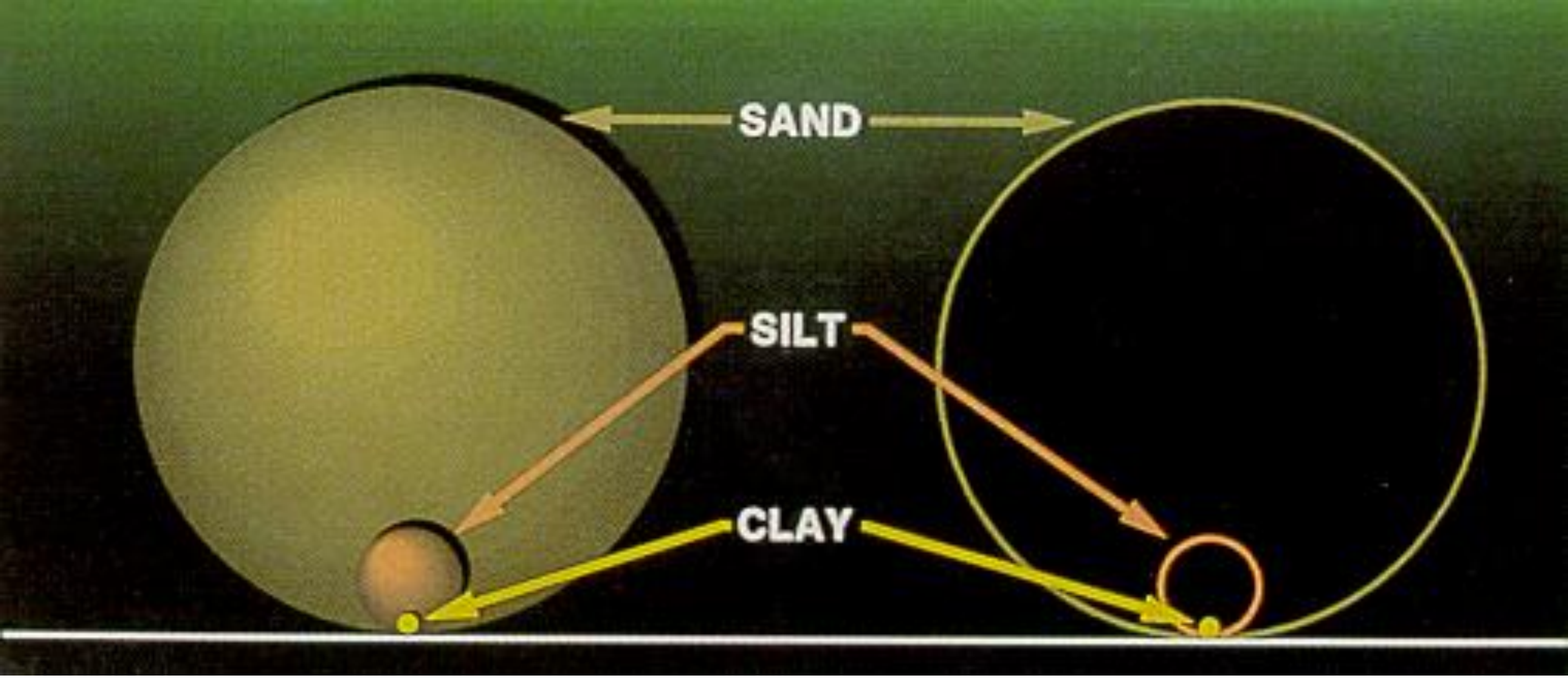
The size distribution is often of critical importance to the way the material performs in use.

Examples

• **Concrete Structures**	**Economical Filler**
• **Roads Construction**	**Bearing Base**
• **Agriculture**	**Infiltration Rate**
• **Environment**	**Filters**

Major Soil Groups



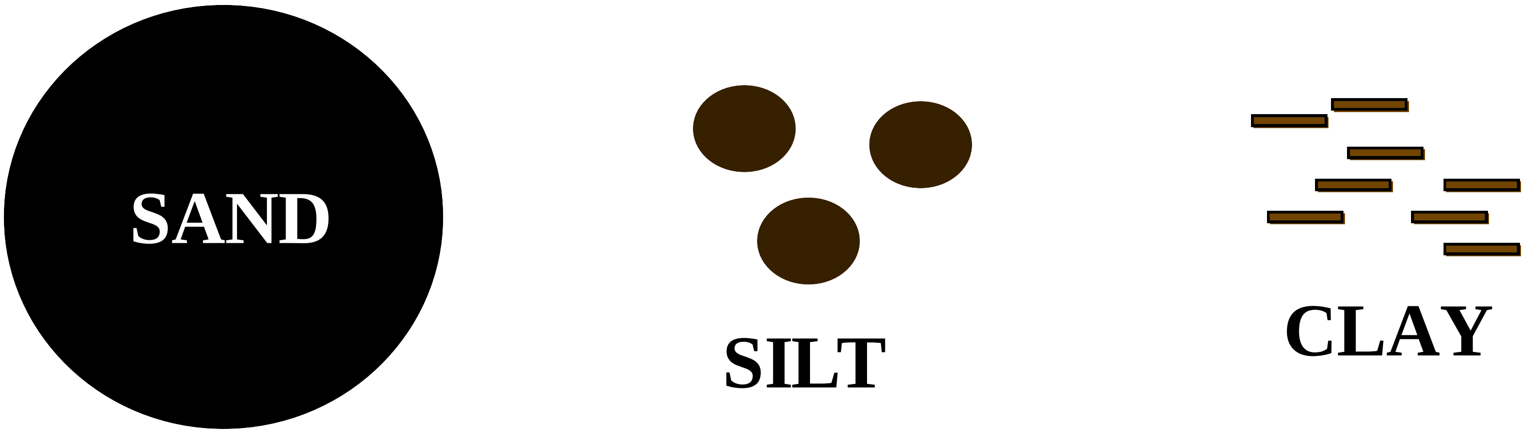


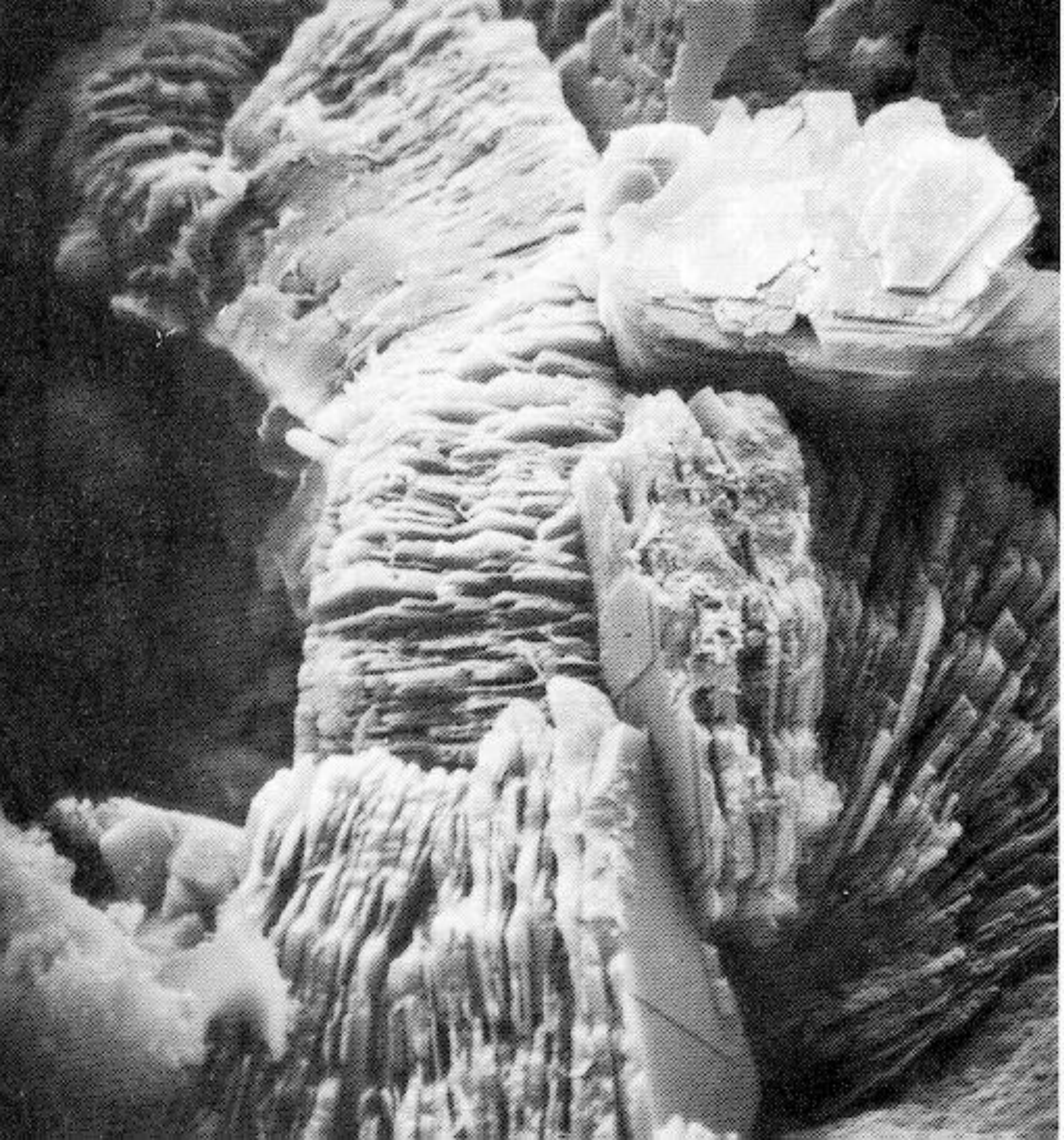
Soil Particles

Note: clays are microscopic in size !

Soil separate particle diameter (mm)

Sand	2.0 - 0.05
Silt	0.05 - 0.002
Clay	<0.002





Clay minerals photographed with an electron Microscope.

Note: they are plate or flake like and are stacked on top of each other.

They are electrically charged and act like magnets that attract and hold plant nutrients.

Note:

Clay-size particles

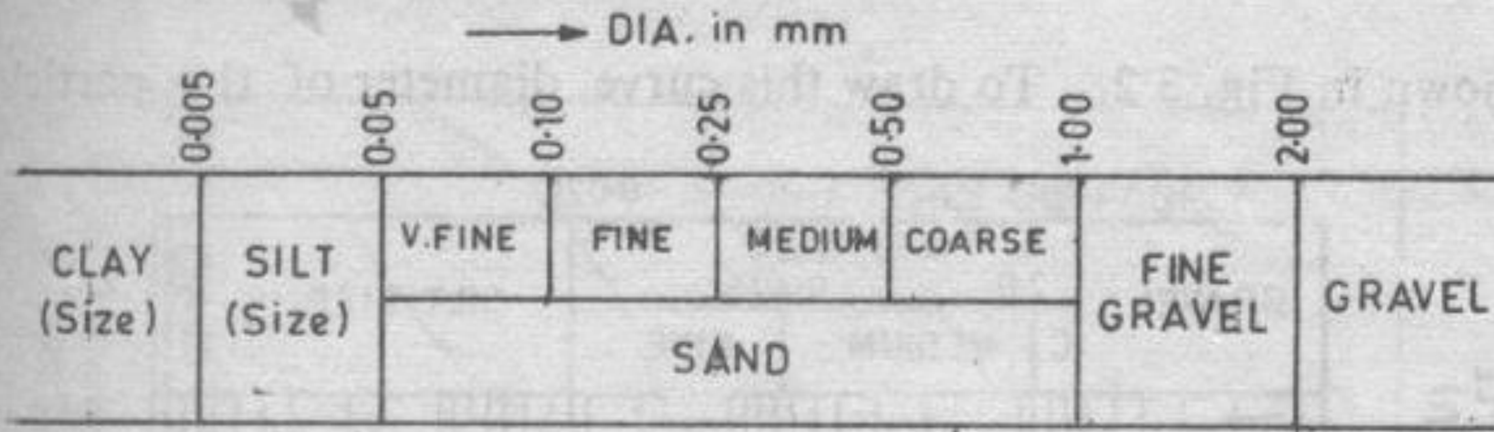
For example:

A small quartz particle may have the similar size of clay minerals.

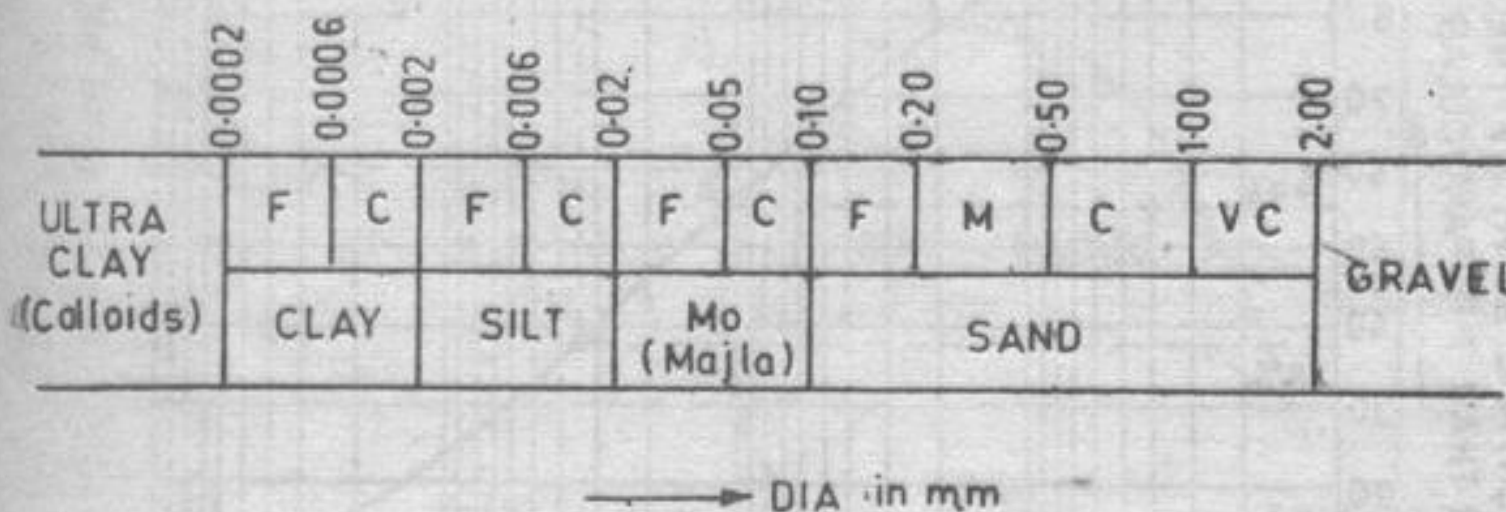
Clay minerals

For example:

Kaolinite, Illite, etc.

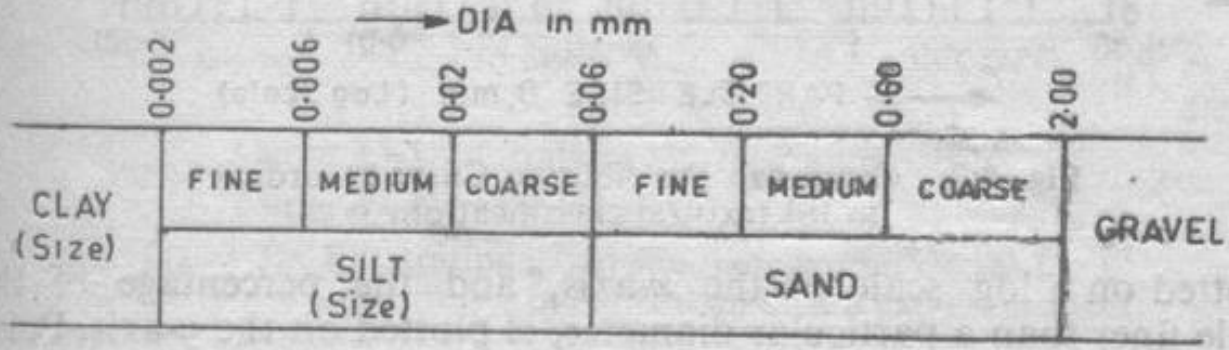


(*a*) U.S. Bureau of Soil and PRA classification.

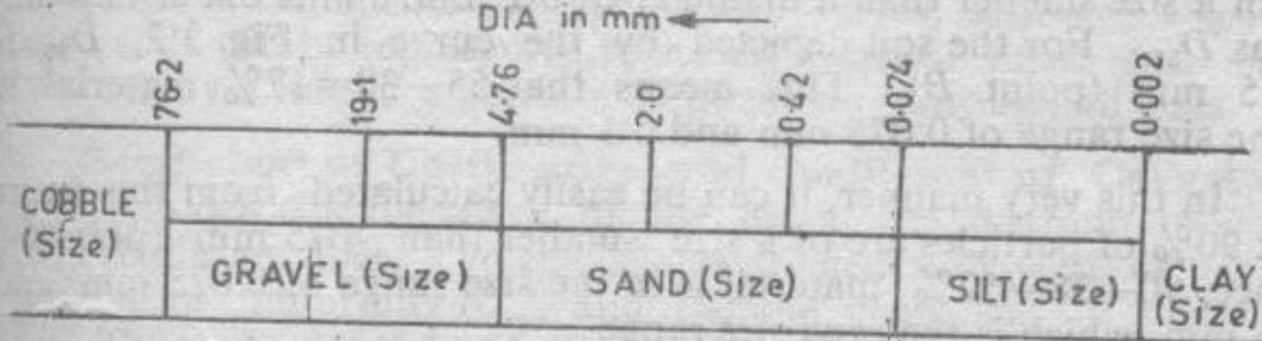


(*b*) International classification.

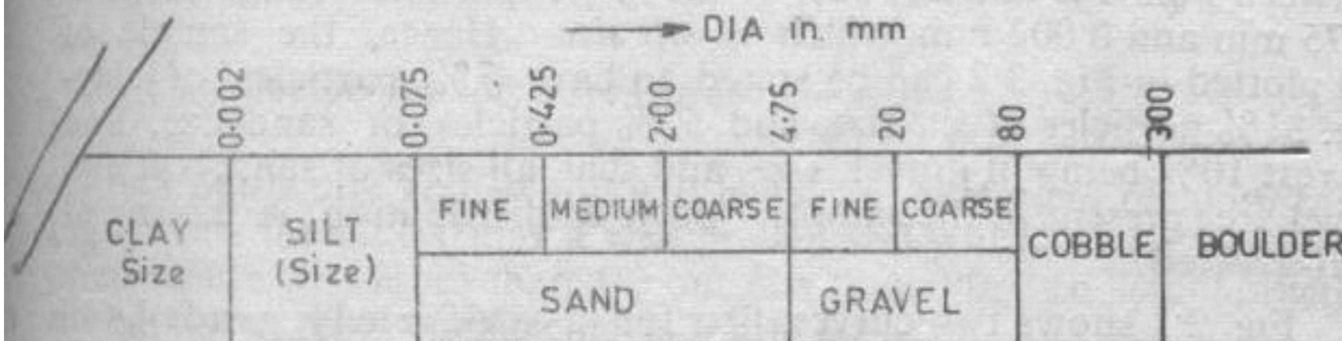
(b) International classification.



(c) M.I.T. classification.



(d) Unified Soil Classification System followed by U.S.B.R. (U.S.A.), Army Coops of Engineers ASTM and ASCE.

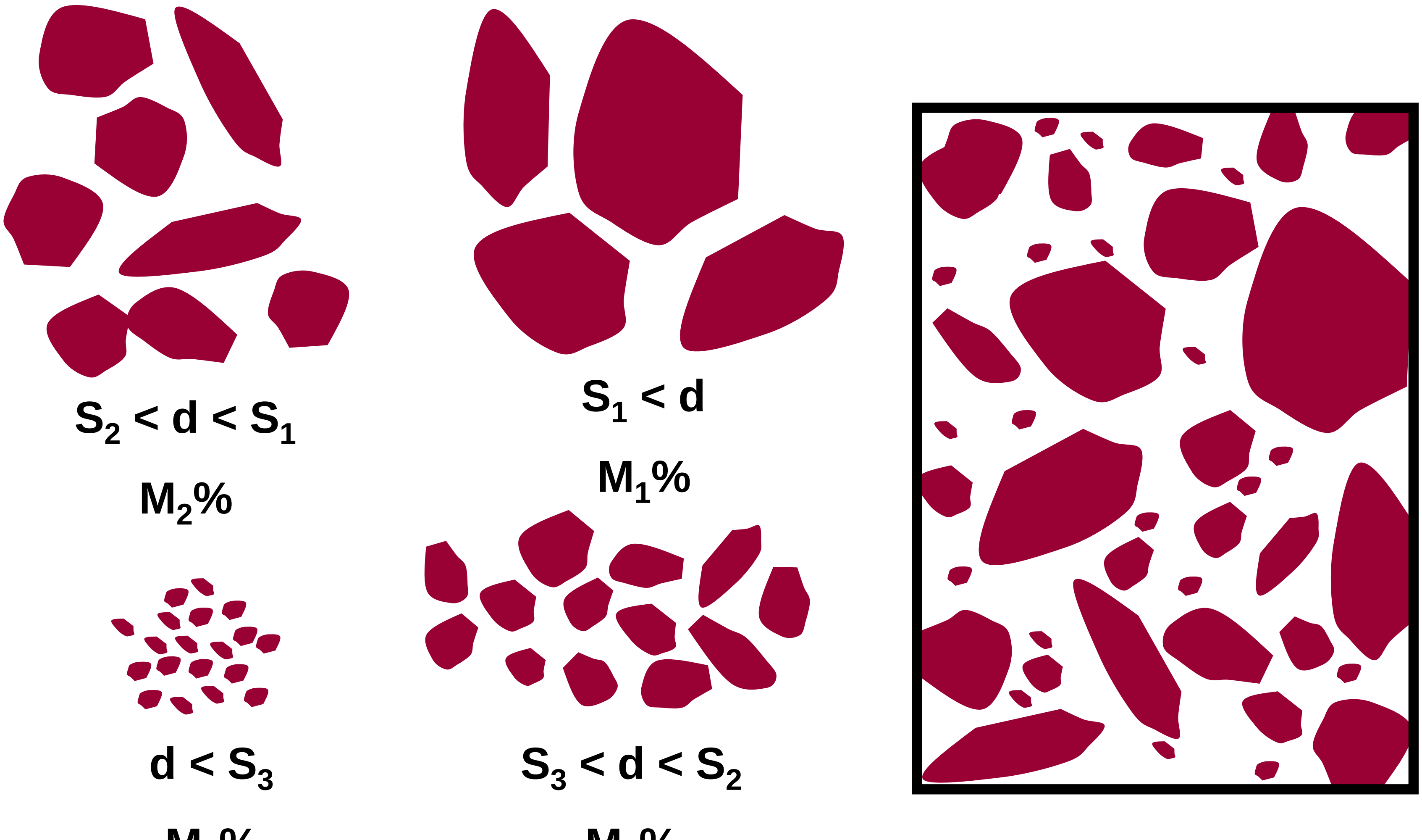


(e) Indian Standard classification.

Content

- Purposes of Grain Size Analysis
- Sieve Analysis
- Hydrometer Analysis
- Particle Distribution
- Shape of Soil Particles

Grain Size Analysis



Particle Size Distribution

- Sieve Analysis
- Sedimentation Analysis

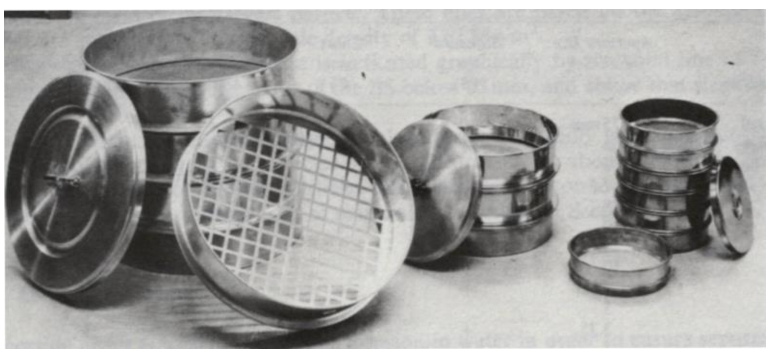
2.2 Grain Size Distribution (Cont.)

- **Experiment**

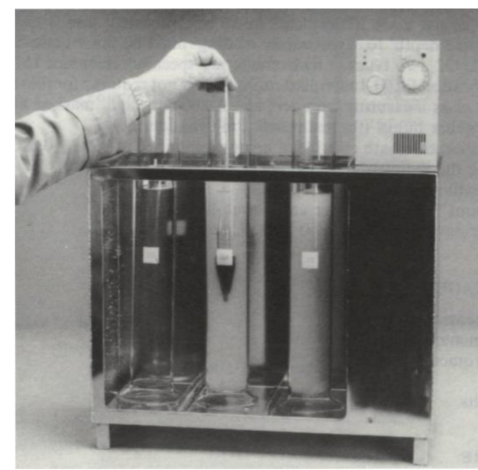
Coarse-grained soils: | Fine-grained soils:

Gravel Sand | Silt Clay

0.075 mm (USCS)



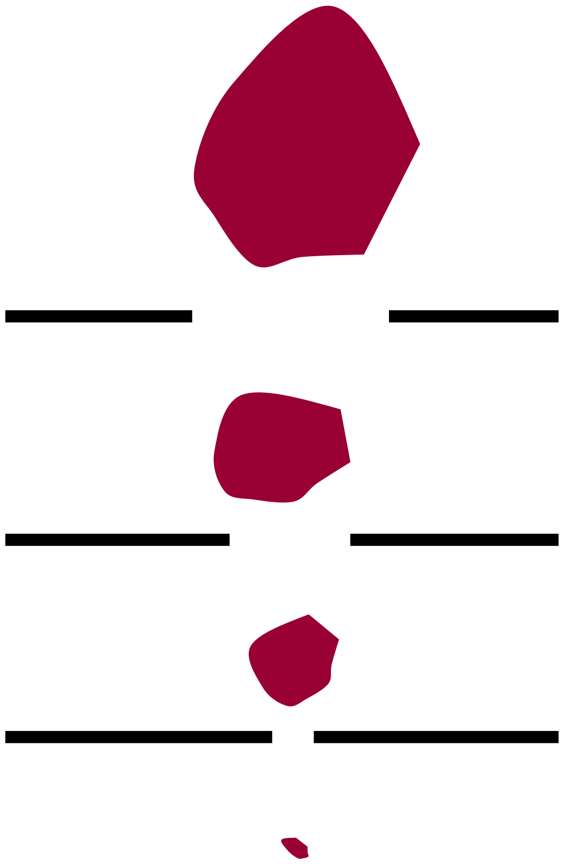
(Head, 1992)



Sieve analysis

Hydrometer analysis

Sieve Analysis



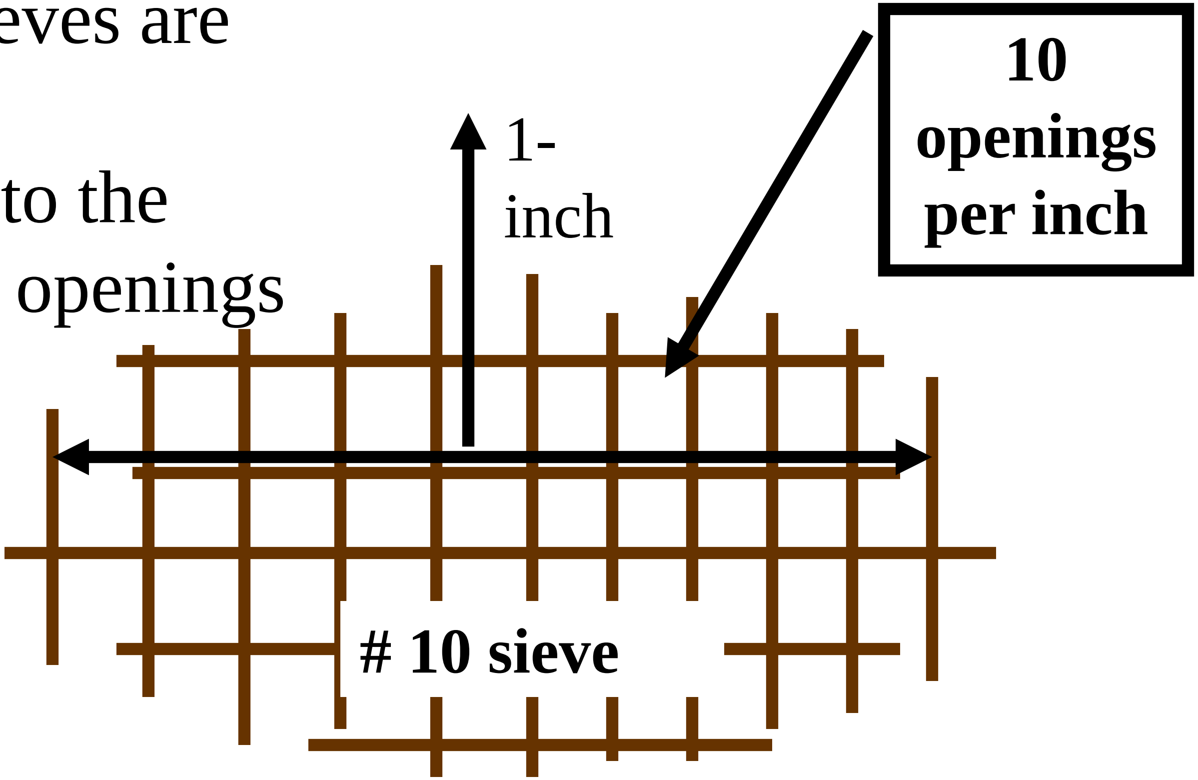
Sieve Analysis

Sieve Designation - Large

Sieves larger than the #4 sieve are designated by the size of the openings in the sieve

Sieve Designation - Smaller

Smaller sieves are numbered according to the number of openings per inch



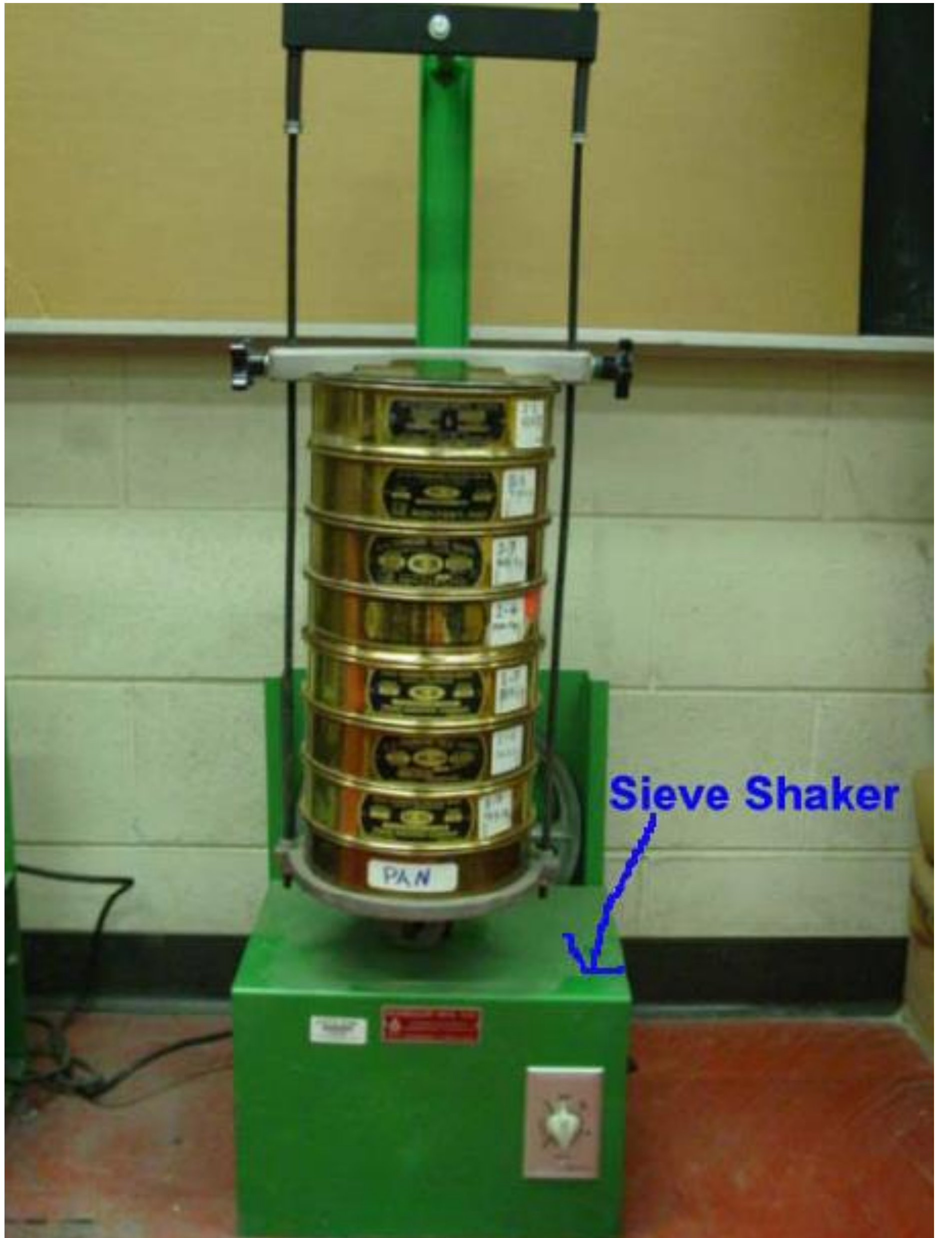
Standard Sieves

Sieve No.	Sieve Opening (mm)
4	4.750
10	2.000
20	0.850
40	0.425
60	0.250
100	0.150
200	0.075

See text book (table 2.5)


Set of Sieves
Soil Specimen
Balance
PAN

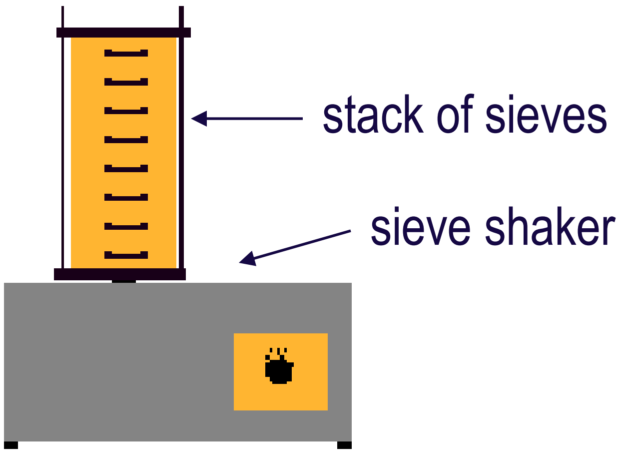
PAN


Sieve Shaker
PAN

Grain Size Distribution

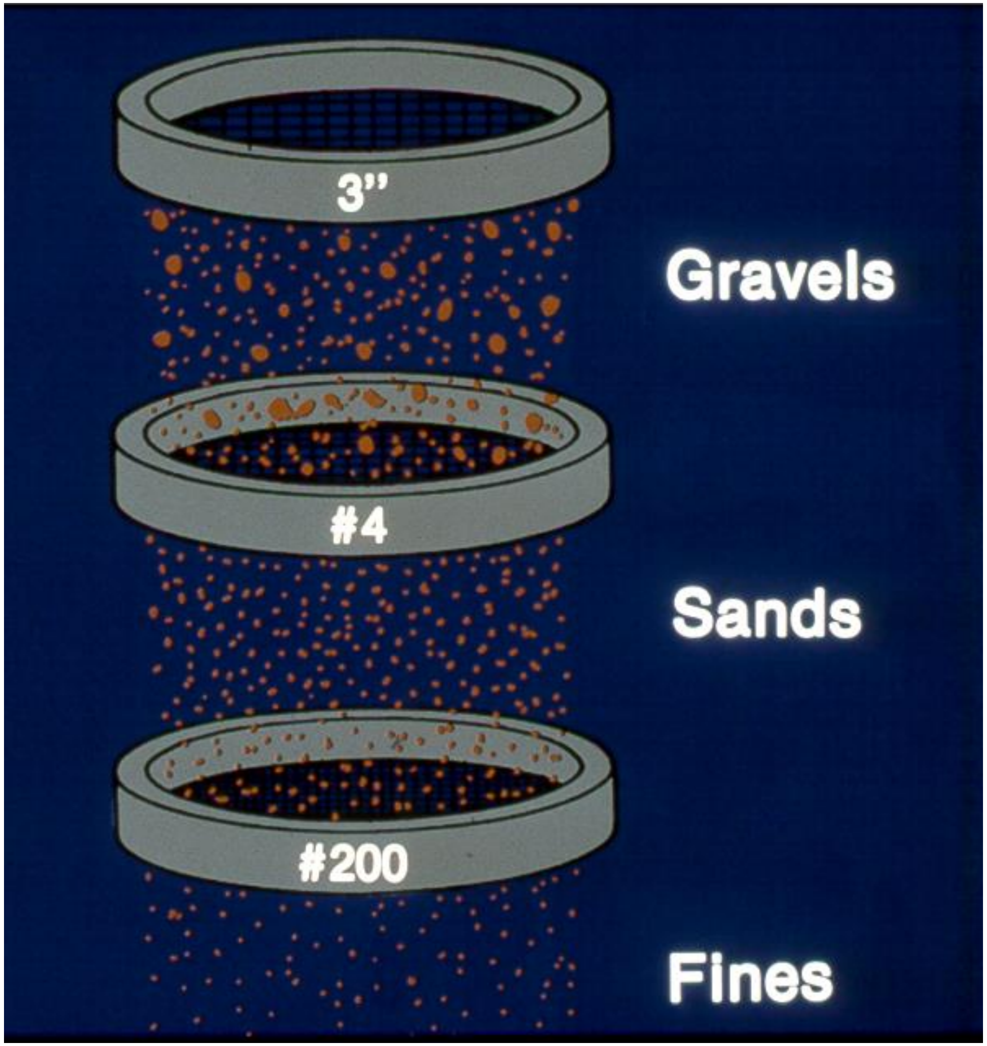
Determination of GSD:

- In coarse grain soils …... By sieve analysis



Sieve Analysis

Sieve Analyses



Sieve Analysis


GEOTEST
ELECTRONIC SOLUTION BALANCE U-1027
0.824
lb
lb/oz
kg
MODE
OFF
SAMPLE
SET
ON
ZERO-TARE
PCS

Percent Finer

Finer (Passing)

76.2 mm — 100 %

Gravel

100 – 93 = 7% Gravel

4.75 mm — 93 %

Sand

93 – 62 = 31% Sand

0.075 mm — 62 %

Silt and Clay

62 – 0 = 62% Silt and Clay

Pan — 0 %

Sieving procedure

(1) Write down the weight of each sieve as well as the bottom pan to be used in the analysis.

(2) Record the weight of the given dry soil sample.

(3) Make sure that all the sieves are clean, and assemble them in the ascending order of sieve numbers (#4 sieve at top and #200 sieve at bottom). Place the pan below #200 sieve. Carefully pour the soil sample into the top sieve and place the cap over it.

(4) Place the sieve stack in the mechanical shaker and shake for 10 minutes.

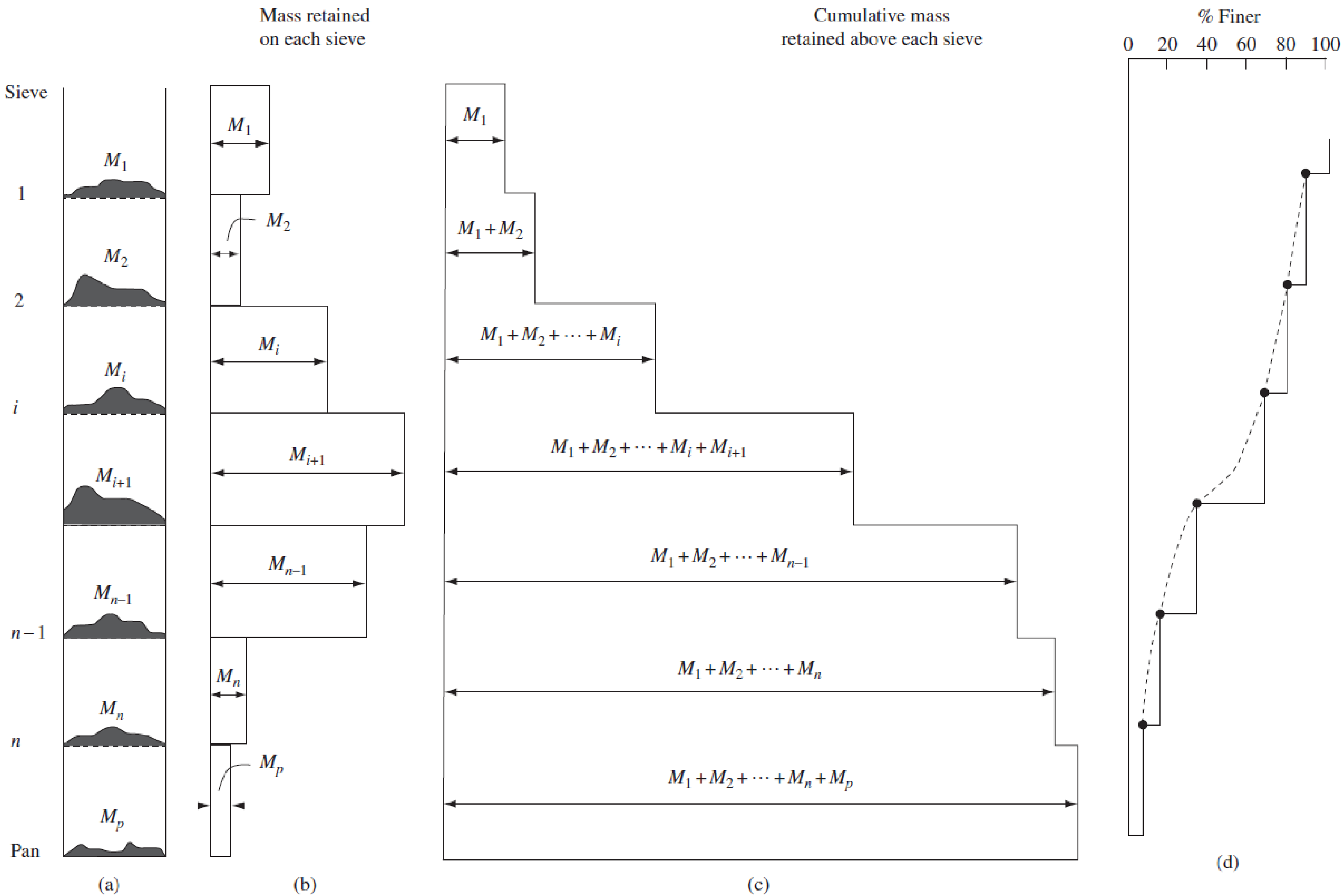
(5) Remove the stack from the shaker and carefully weigh and record the weight of each sieve with its retained soil. In addition, remember to weigh and record the weight of the bottom pan with its retained fine soil.

Data Analysis:

(1) Obtain the mass of soil retained on each sieve by subtracting the weight of the empty sieve from the mass of the sieve + retained soil, and record this mass as the weight retained on the data sheet. The sum of these retained masses should be approximately equals the initial mass of the soil sample. A loss of more than two percent is unsatisfactory.

(2) Calculate the percent retained on each sieve by dividing the weight retained on each sieve by the original sample mass.

(3) Calculate the percent passing (or percent finer) by starting with 100 percent and subtracting the percent retained on each sieve as a cumulative procedure.



Mass retained
on each sieve
Cumulative mass
retained above each sieve
% Finer
0 20 40 60 80 100
Sieve
1
2
i
n − 1
n
Pan
M_1
M_2
M_i
M_{i+1}
M_{n-1}
M_n
M_p
$M_1 + M_2$
$M_1 + M_2 + \cdots + M_i$
$M_1 + M_2 + \cdots + M_i + M_{i+1}$
$M_1 + M_2 + \cdots + M_{n-1}$
$M_1 + M_2 + \cdots + M_n$
$M_1 + M_2 + \cdots + M_n + M_p$
(a)
(b)
(c)
(d)

Sieve Number	Diameter (mm)	Mass of Empty Sieve (g)	Mass of Sieve+Soil Retained (g)	Soil Retained (g)	Percent Retained	Percent Passing
4	4.75	116.23	166.13	49.9	9.5	90.5
10	2. 0	99.27	135.77	36.5	7.0	83.5
20	0.84	97.58	139.68	42.1	8.0	75.5
40	0.425	98.96	138.96	40.0	7.6	67.8
60	0. 25	91.46	114.46	23.0	4.4	63.4
140	0.106	93.15	184.15	91.0	17.4	46.1
200	0.075	90.92	101.12	10.2	1.9	44.1
Pan	---	70.19	301.19	231.0	44.1	0.0
			Total Weight=	523.7		

For example: Total mass = 500 g,

Mass retained on No. 4 sieve = 9.7 g

For the No.4 sieve:

Quantity passing = Total mass - Mass retained

= 500 - 9.7 = 490.3 g

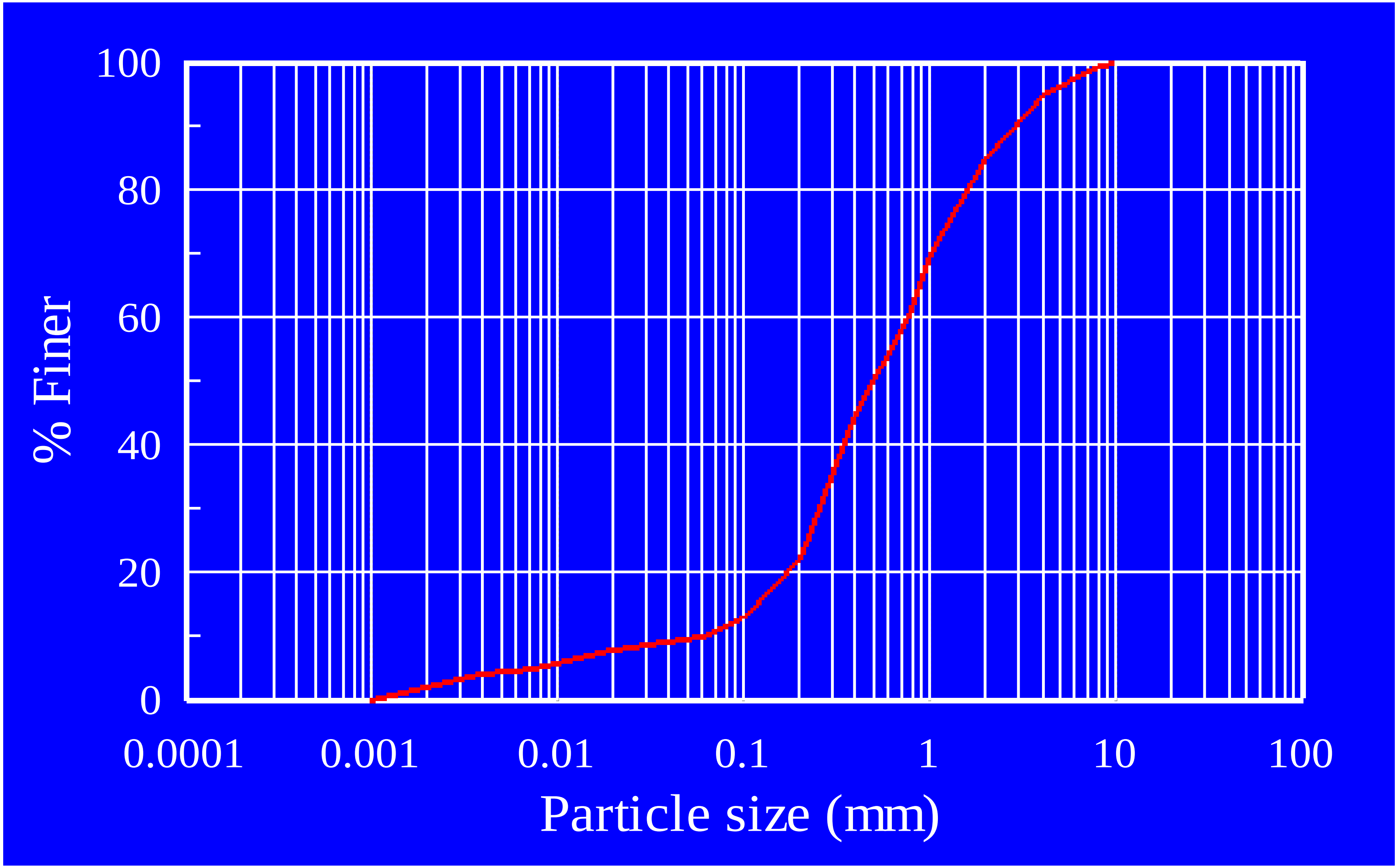
The percent retained is calculated as;

% retained = Mass retained/Total mass

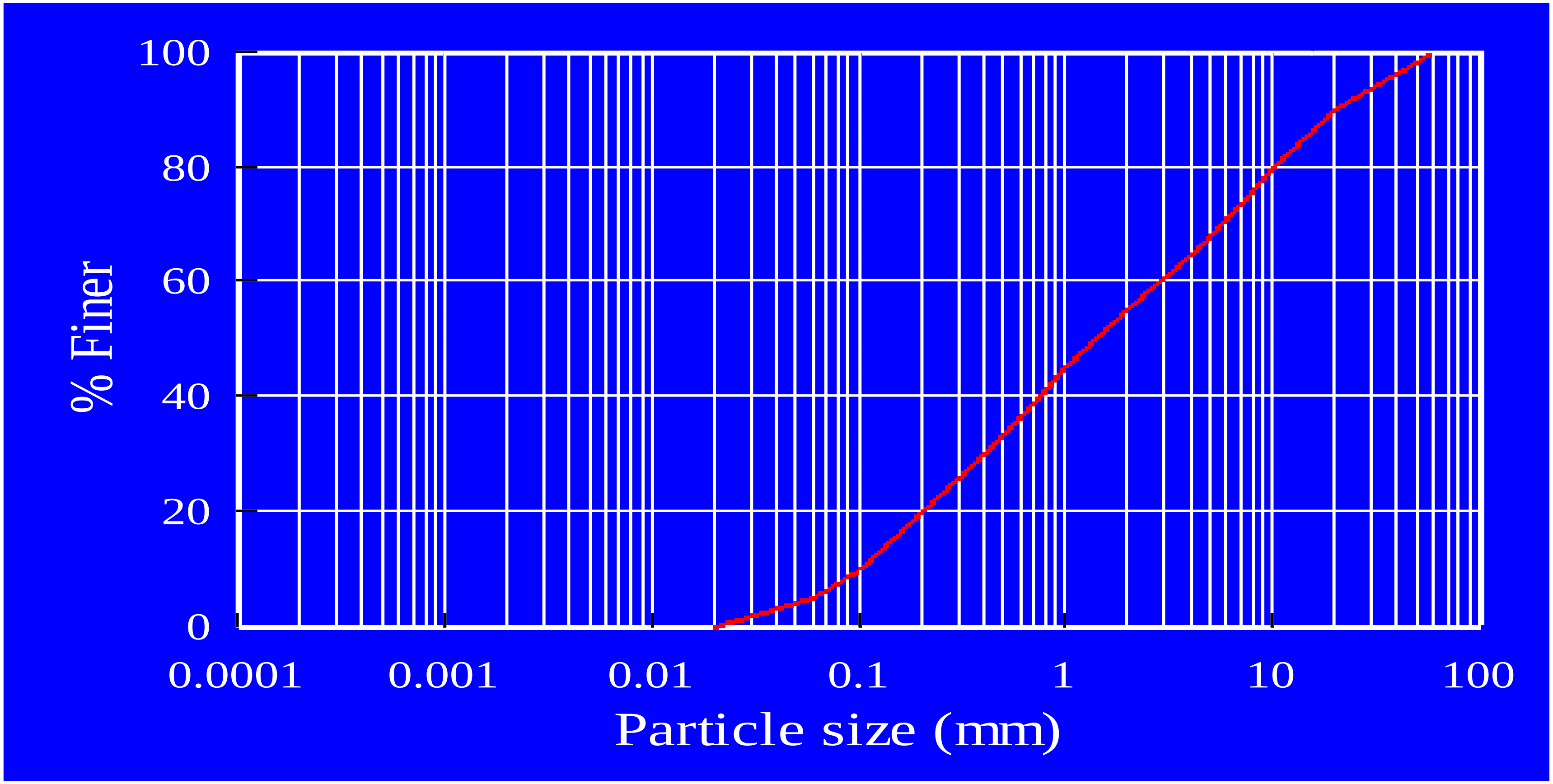
= (9.7/500) X 100 = 1.9 %

From this, the % passing = 100 - 1.9 = 98.1 %

Grain size distribution

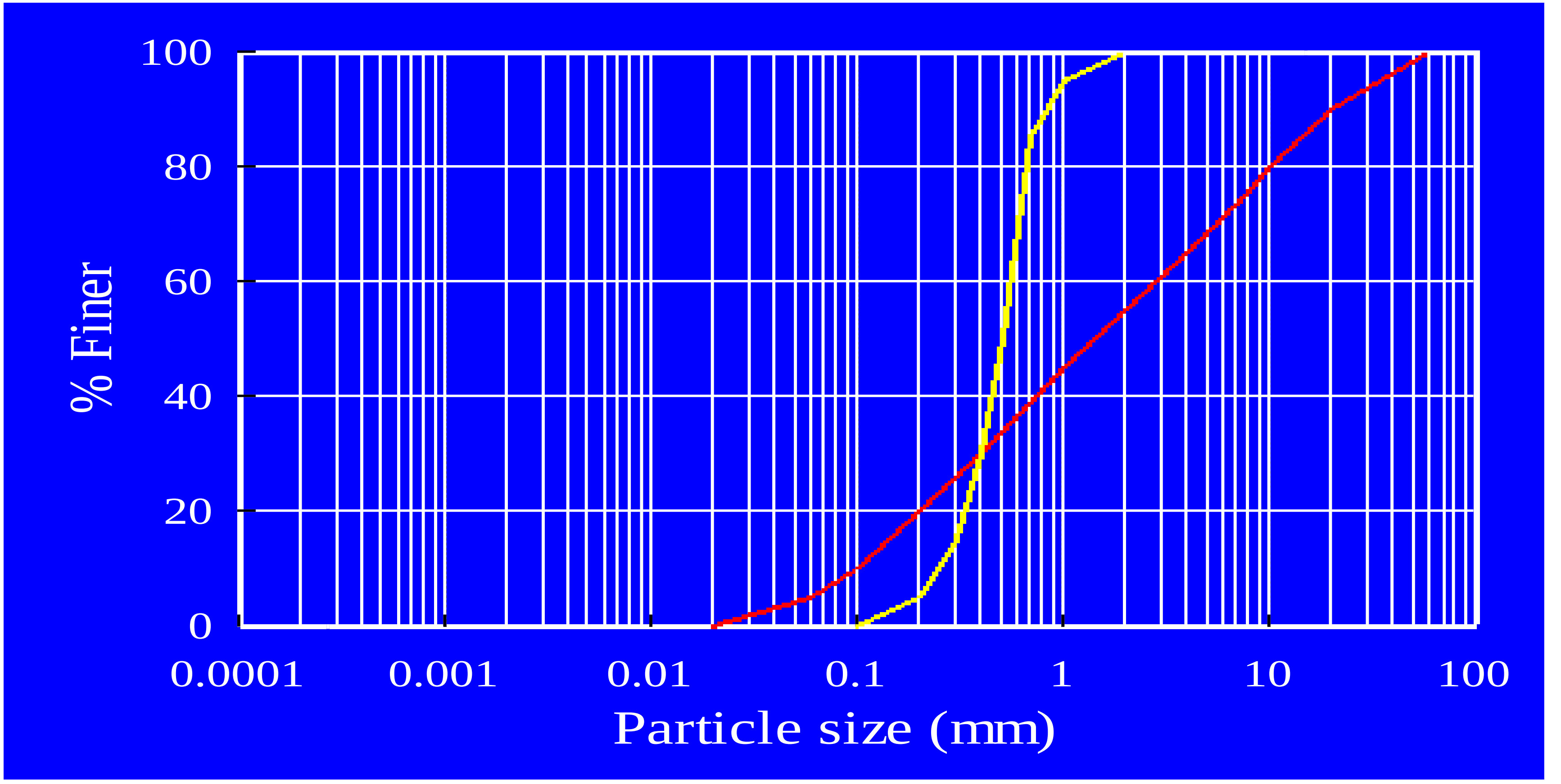


Grading curves



W Well graded

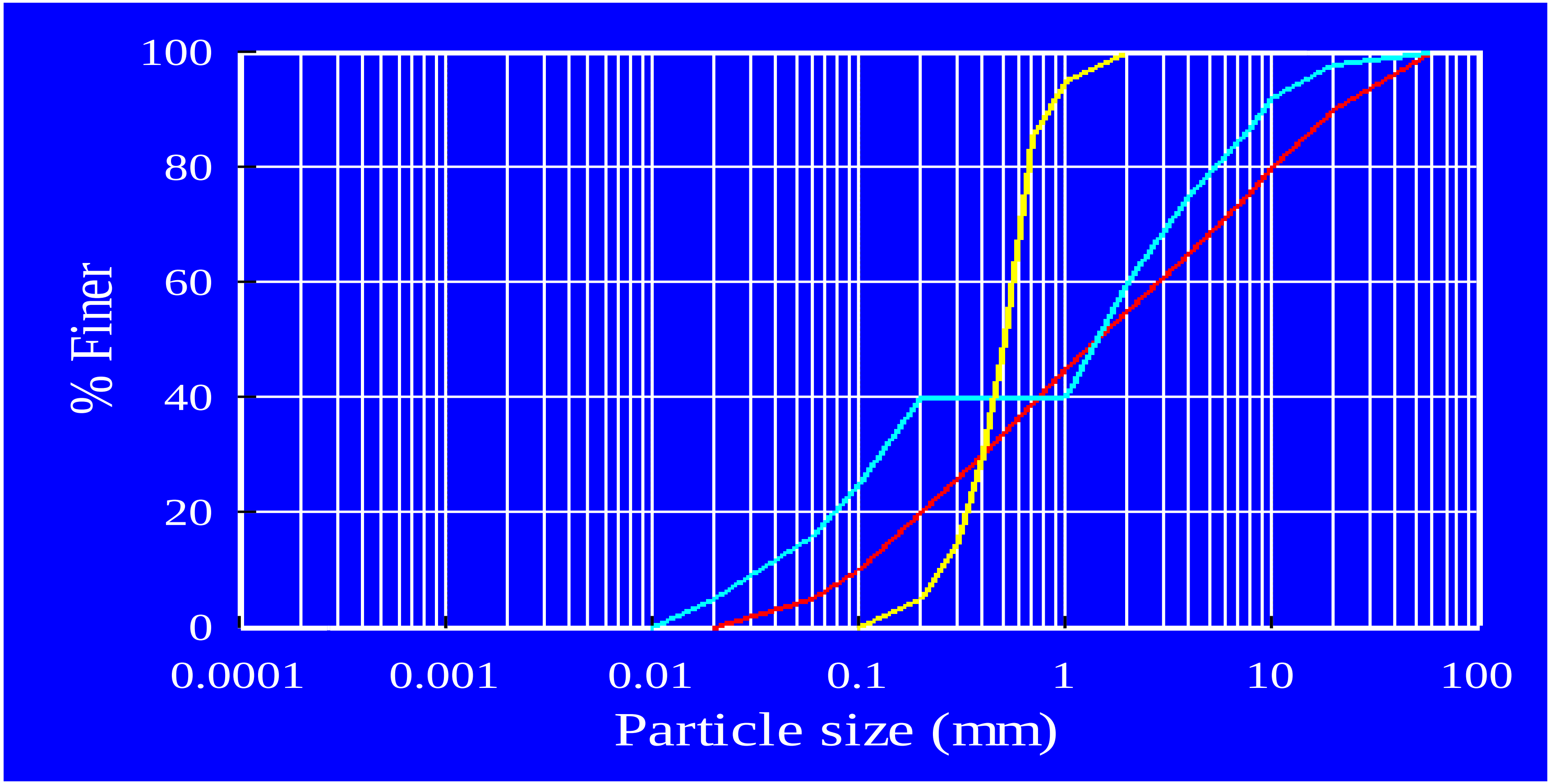
Grading curves



W Well graded

U Uniform

Grading curves

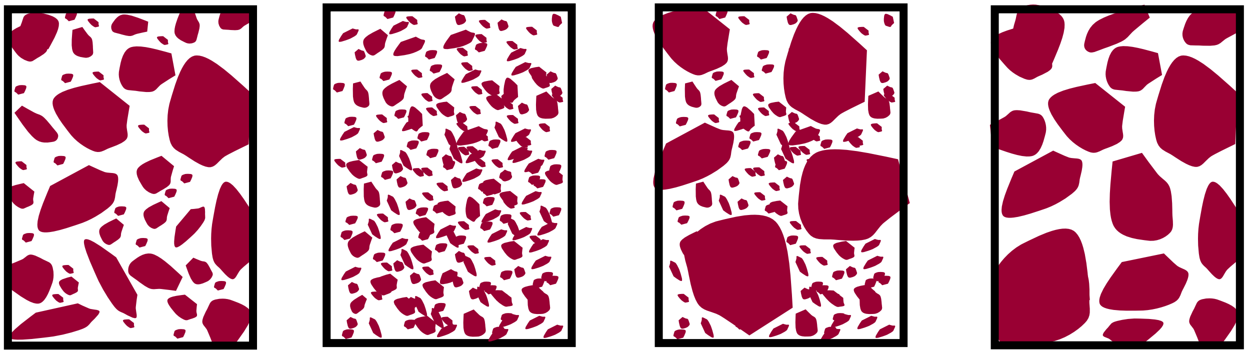


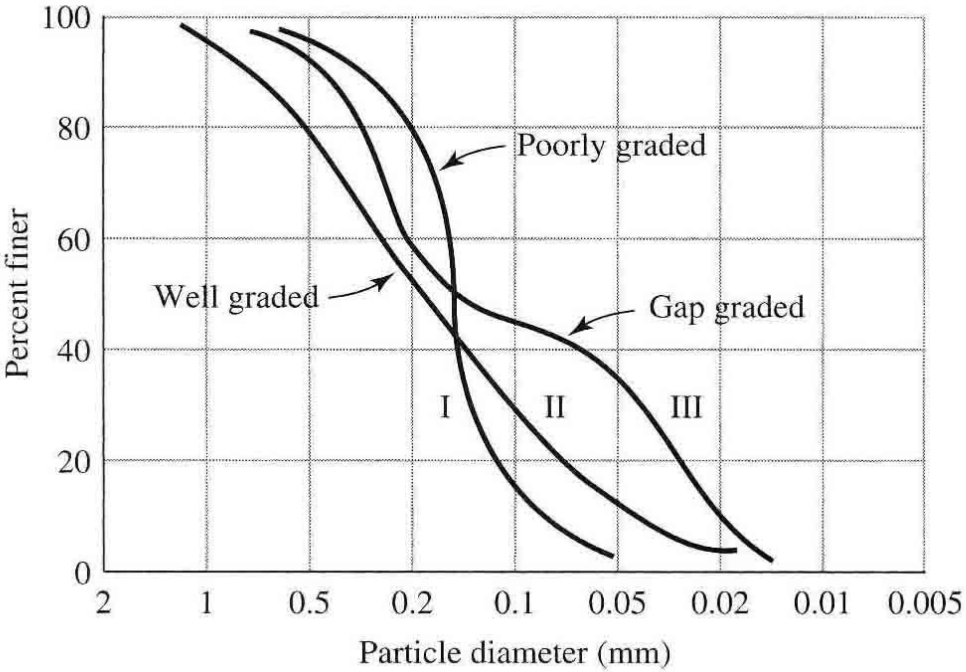
W Well graded

U Uniform

P Poorly graded

Group Work





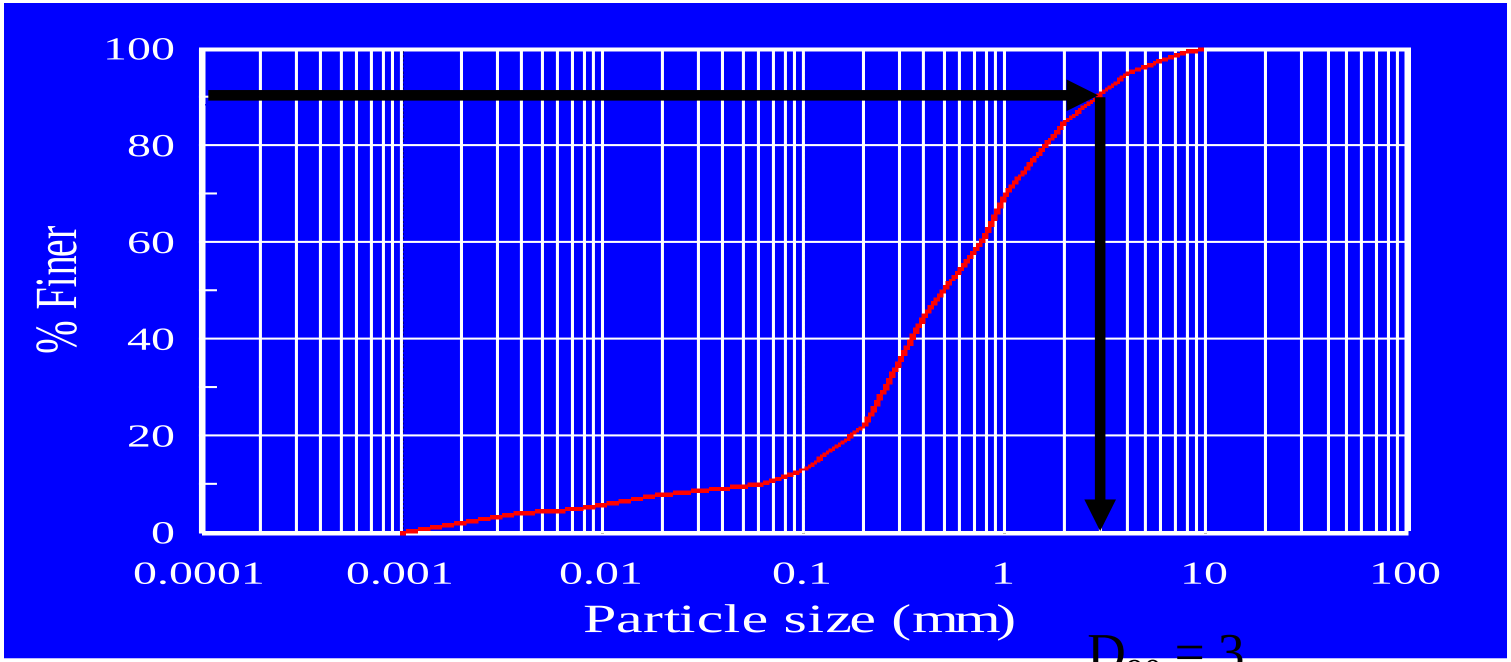
100
80
60
40
20
0
Percent finer
2
1
0.5
0.2
0.1
0.05
0.02
0.01
0.005
Particle diameter (mm)
Poorly graded
Well graded
Gap graded
I
II
III

To determine W or P, calculate C_u and C_c

$$C_u = \frac{D_{60}}{D_{10}}$$

$$C_c = \frac{D_{30}^2}{(D_{60} \times D_{10})}$$

x% of the soil has particles smaller than D_x



$D_{90} = 3$ mm

Grain Size Distribution (Cont.)

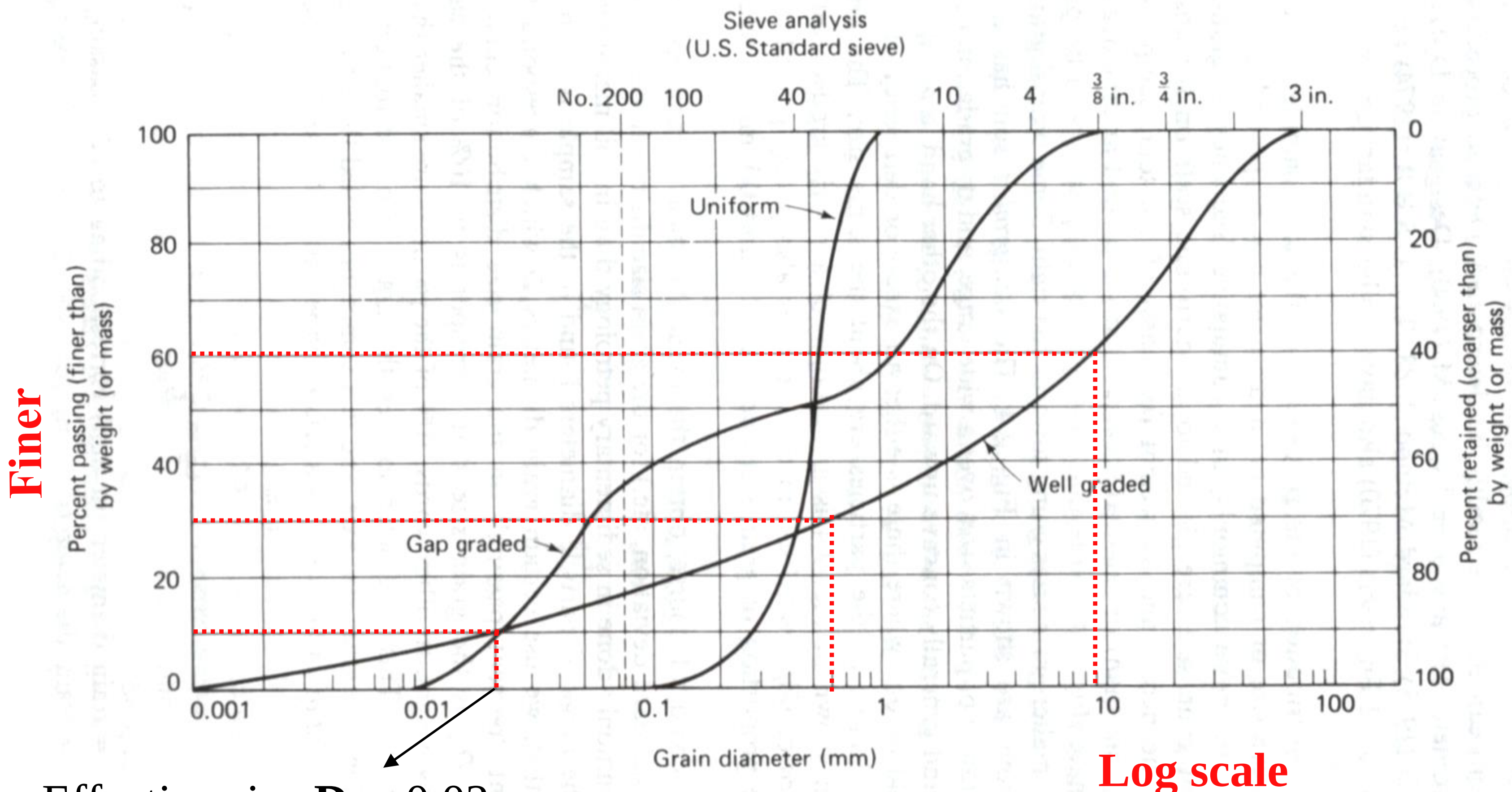


Fig. 2.4 Typical grain size distributions.

Effective size D_{10}: 0.02 mm

D_{30}: D_{60}:

(Holtz and Kovacs, 1981)

Grain Size Distribution (Cont.)

- Describe the shape
  - Example: well graded

$$D_{10} = 0.02\,\text{mm (effective size)}$$
$$D_{30} = 0.6\,\text{mm}$$
$$D_{60} = 9\,\text{mm}$$

Coefficient of uniformity

$$C_u = \frac{D_{60}}{D_{10}} = \frac{9}{0.02} = 450$$

Coefficient of curvature

$$C_c = \frac{(D_{30})^2}{(D_{10})(D_{60})} = \frac{(0.6)^2}{(0.02)(9)} = 2$$

- Criteria

Well-graded soil

$$1 < C_c < 3 \text{ and } C_u \geq 4$$
(for gravels)

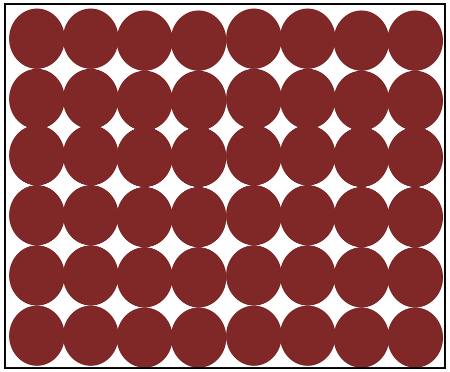
$$1 < C_c < 3 \text{ and } C_u \geq 6$$
(for sands)

- Question
- What is the C_u for a soil with only one grain size?

Particle-Size Distribution Curve

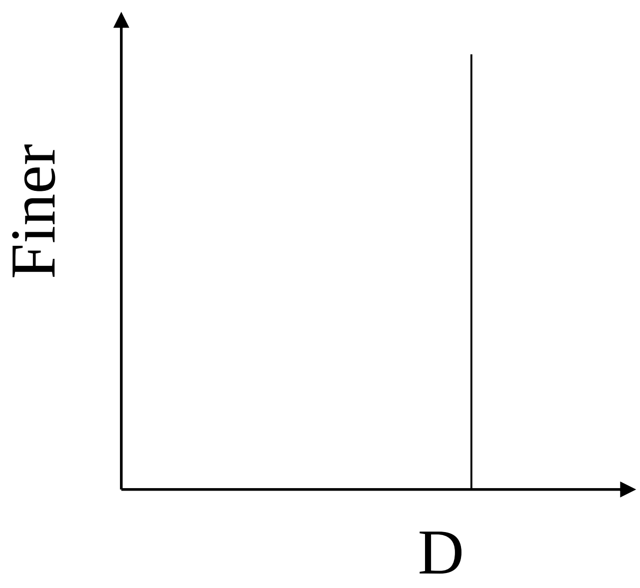
Question

What is the C_u for a soil with only one grain size?



Particle-Size Distribution Curve

Uniformity Coefficient (C_u)



Grain size distribution

Coefficient of uniformity

$$C_u = \frac{D_{60}}{D_{10}} = 1$$

Well or Poorly Graded Soils

Well Graded Soils

Wide range of grain sizes present

Gravels: C_c = 1-3 & C_u >4

Sands: C_c = 1-3 & C_u >6

Poorly Graded Soils

Others, including two special cases:

(a) Uniform soils – grains of same size

(b) Gap graded soils – no grains in a specific size range

Grain Size Distribution

- **Sieve size**

▼ **TABLE 1.5** U.S. Standard Sieve Sizes

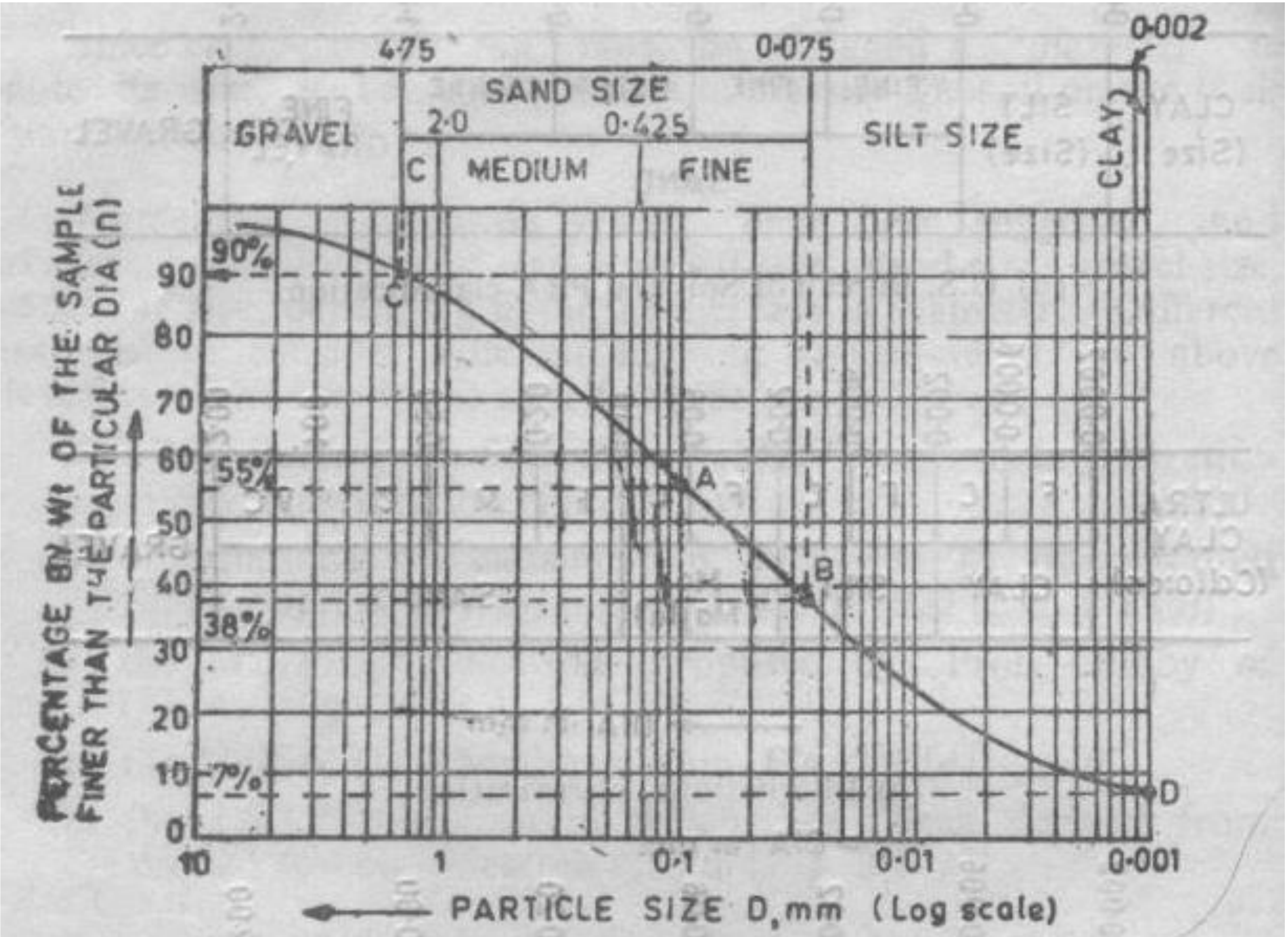
Sieve no.	Opening (mm)
4	4.75
5	4.00
6	3.35
7	2.80
8	2.36
10	2.00
12	1.70
14	1.40
16	1.18
18	1.00
20	0.850
25	0.710
30	0.600
35	0.500
40	0.425
50	0.355
60	0.250
70	0.212
80	0.180
100	0.150
120	0.125
140	0.106
170	0.090
200	0.075
270	0.053

(Das, 1998)

Table 4.5(a). METRIC SIEVES (BS)

Construction	*Aperture size: Full Set (A)*	*'Standard' set (B)*	*'Short' set C)*
Perforated steel place (square hole)	75 mm	+	
	63	+	+
	50		
	37.5	+	
	28		
	20	+	+
	14		
	10	+	
	6.3	+	+
	5		
	3.35	+	
	2	+	+
	1.18	+	
	600 μm	+	+
	425		
	300	+	
	212		+
	150	+	
	63	+	+
Lid and receiver	+	+	+
	19 sieves	13 sieves	7 sieves

(Head, 1992)



4·75
0·075
0·002
SAND SIZE
2·0
0·425
GRAVEL
SILT SIZE
CLAY
C
MEDIUM
FINE
90%
55%
38%
7%
A
B
C
D
90
80
70
60
50
40
30
20
10
0
10
1
0·1
0·01
0·001
PERCENTAGE BY Wt OF THE SAMPLE FINER THAN THE PARTICULAR DIA (n)
PARTICLE SIZE D, mm (Log scale)

Engineering applications of GSD

- It will help us “feel” the soil texture (what the soil is) and it will also be used for the soil classification (next topic).
- It can be used to define the grading specification of a drainage filter (clogging).
- It can be a criterion for selecting fill materials of embankments and earth dams, road sub-base materials, and concrete aggregates.
- It can be used to estimate the results of grouting and chemical injection, and dynamic compaction.
- Effective Size, D_{10}, can be correlated with the hydraulic conductivity (describing the permeability of soils). (Hazen’s Equation).(Note: controlled by small particles)

Grain Size Distribution

Significance of GSD:

- To know the relative proportions of different grain sizes.

- An important factor influencing the geotechnical characteristics of a **coarse** grain soil.

- Not important in fine grain soils.

Example: Sieve Analysis

Example 2.1

Following are the results of a sieve analysis. Make the necessary calculations and draw a particle-size distribution curve.

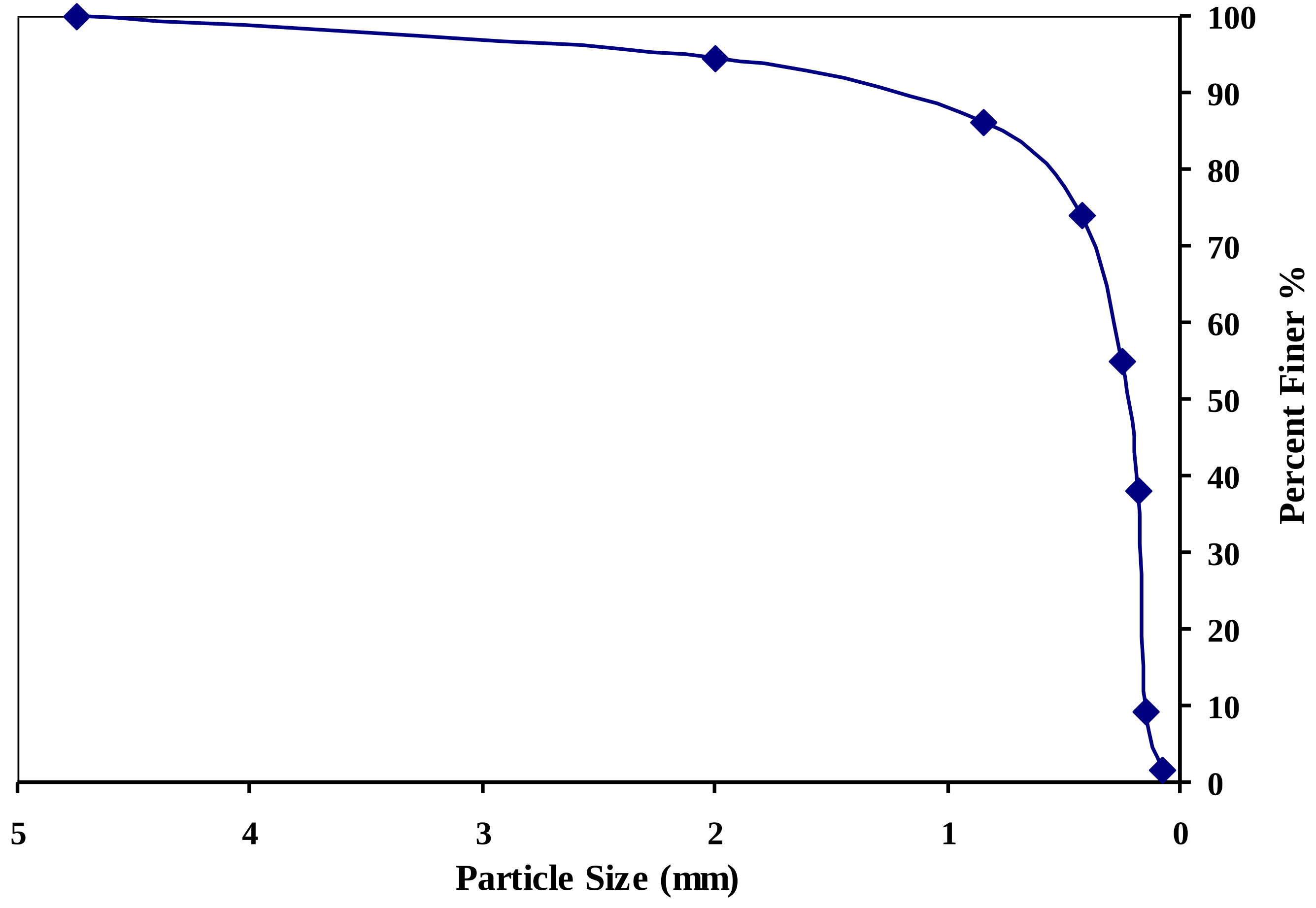
U.S. sieve size	Mass of soil retained on each sieve (g)
4	0
10	40
20	60
40	89
60	140
80	122
100	210
200	56
Pan	12

Example: Sieve Analysis

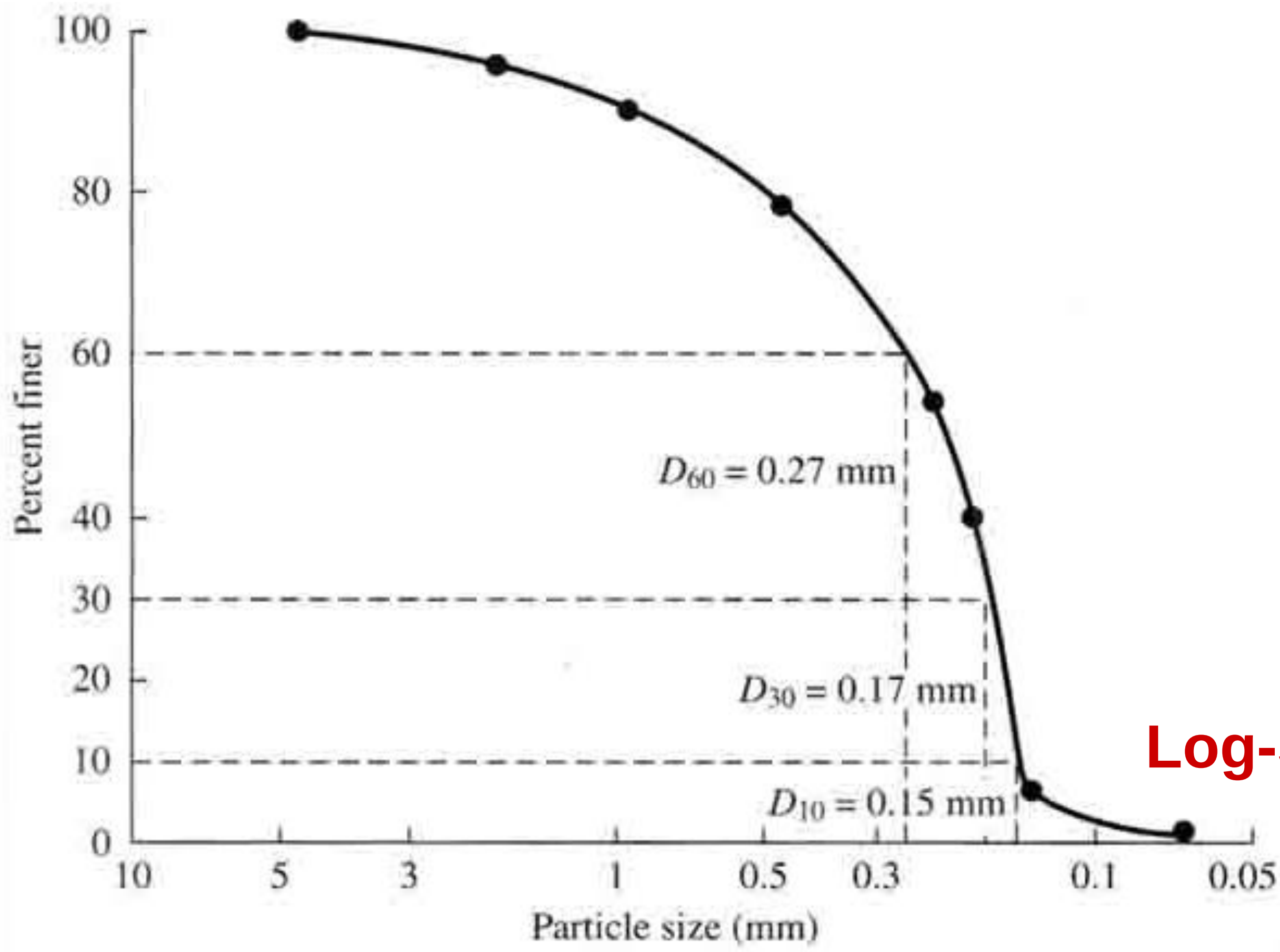
U.S. sieve (1)	Opening (mm) (2)	Mass retained on each sieve (g) (3)	Cumulative mass retained above each sieve (g) (4)	Percent finer[a] (5)
4	4.75	0	0	**100**
10	2.00	40	0 + 40 = 40	**94.5**
20	0.850	60	40 + 60 = 100	**86.3**
40	0.425	89	100 + 89 = 189	**74.1**
60	0.250	140	189 + 140 = 329	**54.9**
80	0.180	122	329 + 122 = 451	**38.1**
100	0.150	210	451 + 210 = 661	**9.3**
200	0.075	56	661 + 56 = 717	**1.7**
Pan	—	12	717 + 12 = 729 = ΣM	**0**

[a] $\dfrac{\Sigma M - \text{col. 4}}{\Sigma M} \times 100 = \dfrac{729 - \text{col. 4}}{729} \times 100$

Example: Sieve Analysis

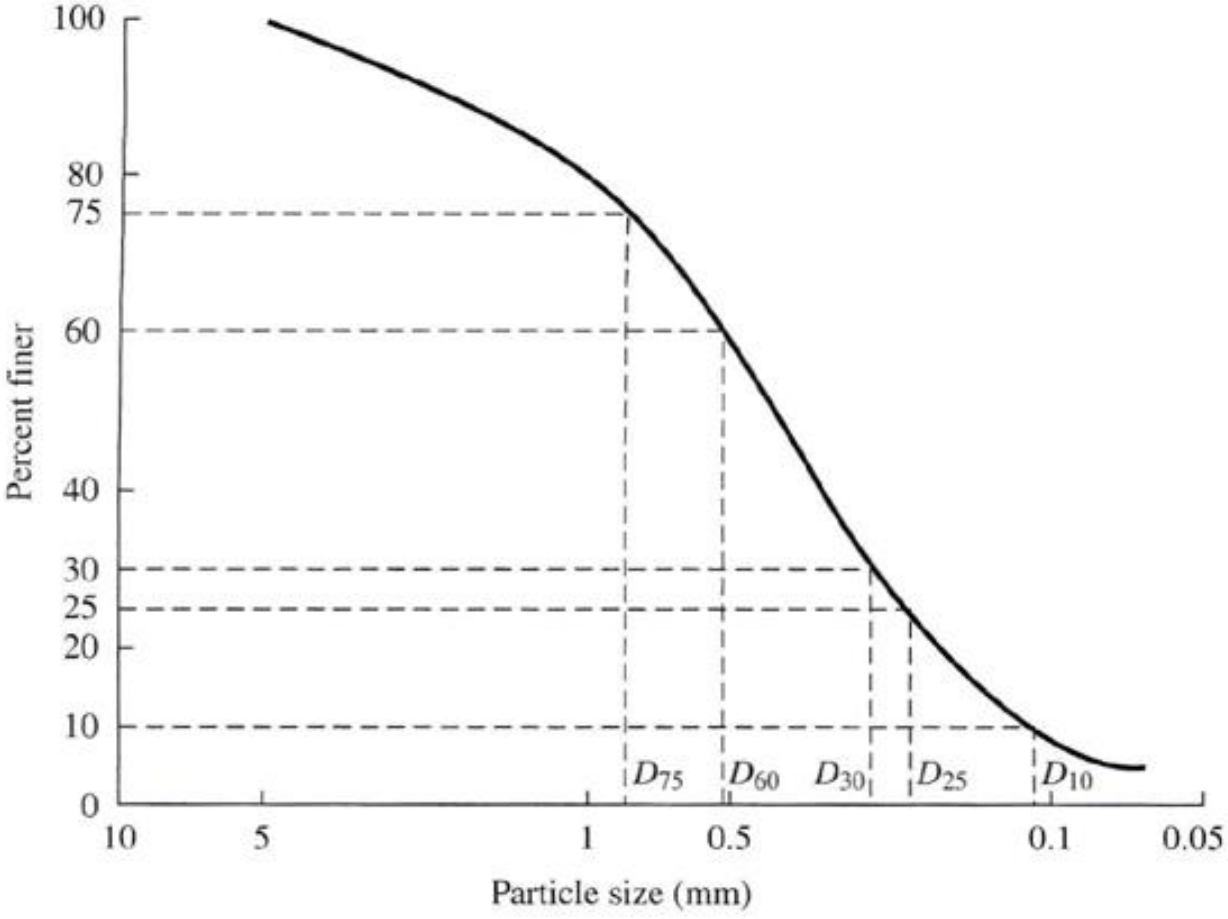


Example: Sieve Analysis

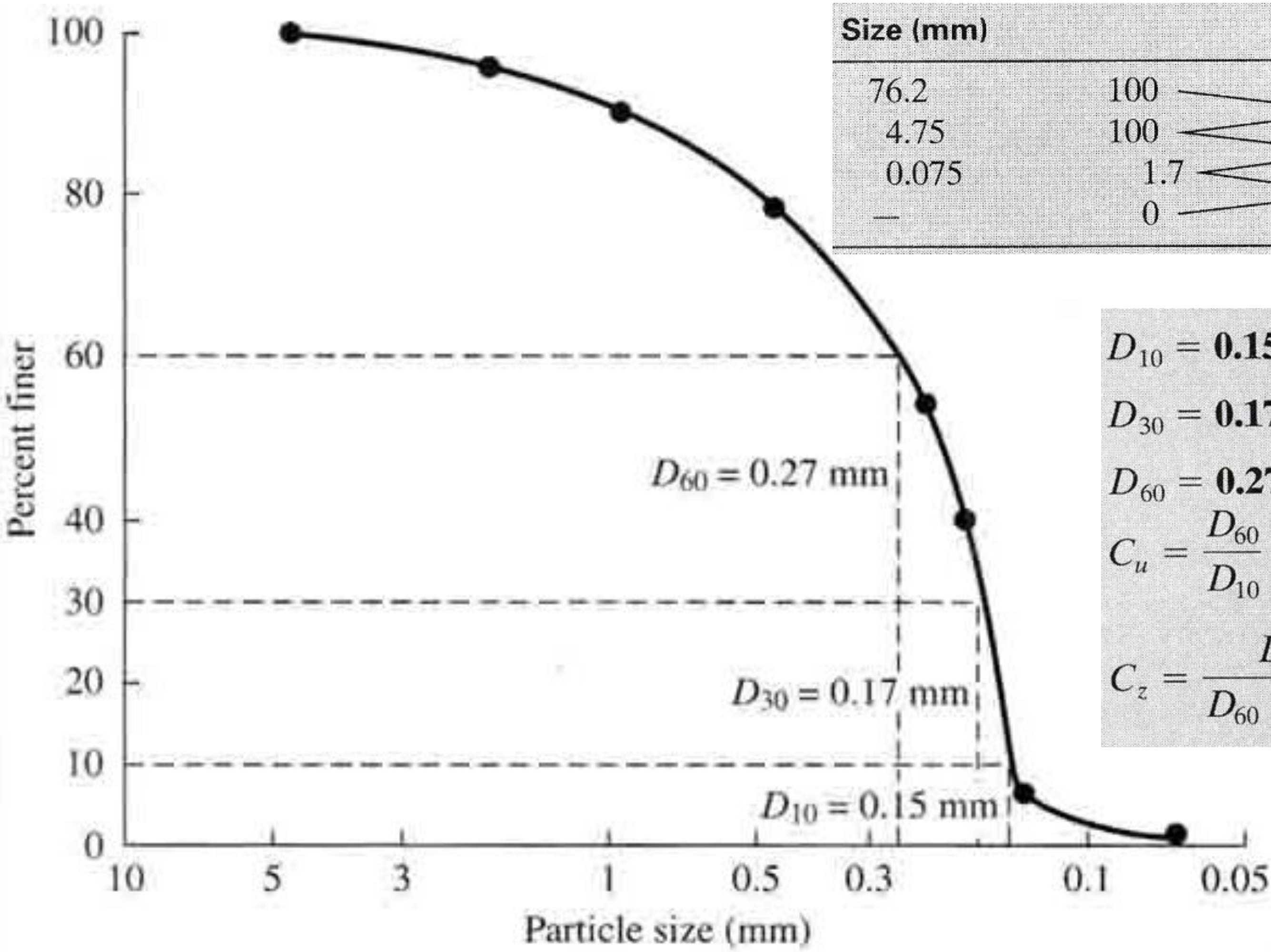


Log-Scale

Particle-Size Distribution Curve



Particle-Size Distribution Curve



Size (mm)	% finer	
76.2	100	100 − 100 = **0% gravel**
4.75	100	100 − 1.7 = **98.3% sand**
0.075	1.7	1.7 − 0 = **1.7% silt and clay**
—	0	

D_{10} = **0.15 mm**

D_{30} = **0.17 mm**

D_{60} = **0.27 mm**

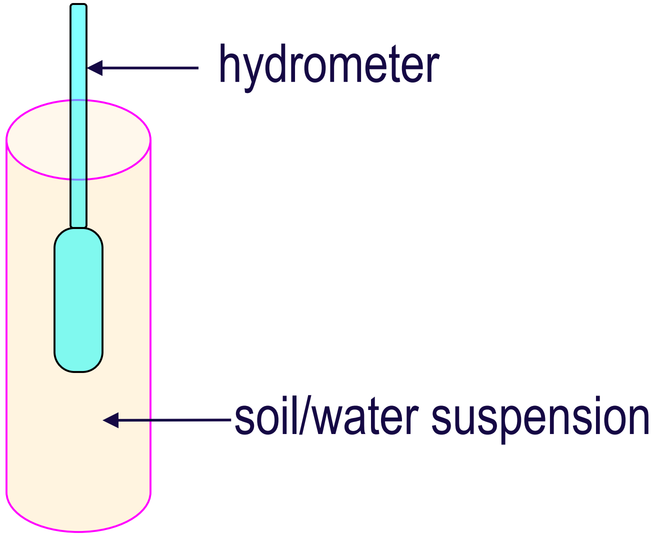
$$C_u = \frac{D_{60}}{D_{10}} = \frac{0.27}{0.15} = \mathbf{1.8}$$

$$C_z = \frac{D_{30}^2}{D_{60} \times D_{10}} = \frac{(0.17)^2}{(0.27)(0.15)} = \mathbf{0.71}$$

Grain Size Distribution

Determination of GSD:

- In fine grain soils …… By hydrometer analysis



Hydrometer Analysis

6. Some Thoughts about the Hydrometer Analysis

Stokes' law

$$v = \frac{(\gamma_s - \gamma_w)D^2}{18\eta}$$

Assumption	Reality
Sphere particle	Platy particle (clay particle) as D ≤ *0.005mm*
Single particle (No interference between particles)	Many particles in the suspension
Known specific gravity of particles	Average results of all the minerals in the particles, including the adsorbed water films. ***Note:*** the adsorbed water films also can increase the resistance during particle settling.
Terminal velocity	Brownian motion as D ≤ *0.0002 mm*

(Compiled from Lambe, 1991)

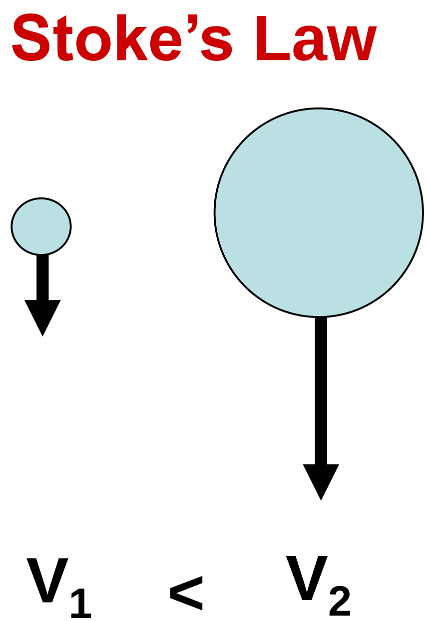
Example: Some shapes of soil particles

Rounded

Angular

Stoke's Law

Based on the principle of sedimentation of soil grains in water.



$$v = \frac{D^2}{18\eta} \cdot [\gamma_s - \gamma_w]$$

$$D^2 = \left[\frac{18 \cdot \eta \cdot v}{\gamma_s - \gamma_w} \right]$$

$$D = \sqrt{\frac{18\,\eta \cdot v}{\gamma_s - \gamma_w}}$$

$$D = \sqrt{\frac{18 \,.\, \eta \,.\, v}{\gamma_w \,(G - 1)}}$$

Table 3.4. Important Properties of Water in S.I. Units

Temp. °*C*	*Sp. gravity*	*Unit wt. in* kN/m^3 *i.e. Sp. gravity* × *9.807*	*Vapour pressure in* kN/m^2	*Viscosity*	
				Dynamic (η) *in* kNs/m^2 [$1\ kN.s/m^2 = 10^4$ *Poise*]	*Kinematic* (ν) *in* m^2/sec [$1\ m^2/s = 10^4$ *Stoke*] *(St)*]
(1)	(2)	(3)	(4)	(5)	(6)
0	0.99987	9.806	0.61	1.797×10^{-6}	1.78×10^{-6}
5	0.99999	9.807	0.87	1.518×10^{-6}	1.518×10^{-6}
10	0.99975	9.805	1.23	1.307×10^{-6}	1.310×10^{-6}
15	0.99907	9.798	1.70	1.126×10^{-6}	1.124×10^{-6}
20	**0.99810**	**9.788**	**2.33**	$\mathbf{1.004 \times 10^{-6}}$	$\mathbf{1.009 \times 10^{-6}}$
30	0.99574	9.765	4.61	0.802×10^{-6}	0.804×10^{-6}
40	0.99228	9.731	7.60	0.652×10^{-6}	0.654×10^{-6}
60	0.98338	9.644	19.94	0.470×10^{-6}	0.478×10^{-6}
80	0.97196	9.532	46.60	0.356×10^{-6}	0.366×10^{-6}
100	0.95865	9.401	101.53	0.283×10^{-6}	0.295×10^{-6}

In case soil analysis is done in water

- Unit weight of water = 9.81 kN/m^3
- Let specific gravity of soil=2.65
- Viscosity of water at 20oC= 1.004x10-6 kN-sec/m^2

Then

$$D_{cm} = 0.106\sqrt{v}$$

$$D_{mm} = 1.06\sqrt{v}$$

$$\sqrt{v} = \frac{1}{1.06} D_{mm}$$

V is in m/sec

$$v_{m/sec} = \frac{1}{(1.06)^2} D_{mm}{}^2$$

$$v_{m/sec} = 0.89 \times D_{mm}{}^2$$

$$v_{cm/sec} = 89\, D_{mm}{}^2$$

Example

Find the time taken by a soil particle of diameter 10 micron (10×10^{-6} m$=10^{-5}$ m$=0.001$ cm) from the surface to the bottom of a pond 3 m deep. Assume the specific gravity of soil is 2.65 and viscosity of water=0.01poise

Hydrometer Analysis

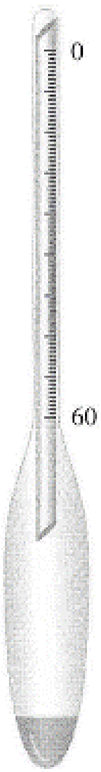


Figure 2.16
ASTM 152H hydrometer
(courtesy of Soiltest, Inc.,
Lake Bluff, Illinois)

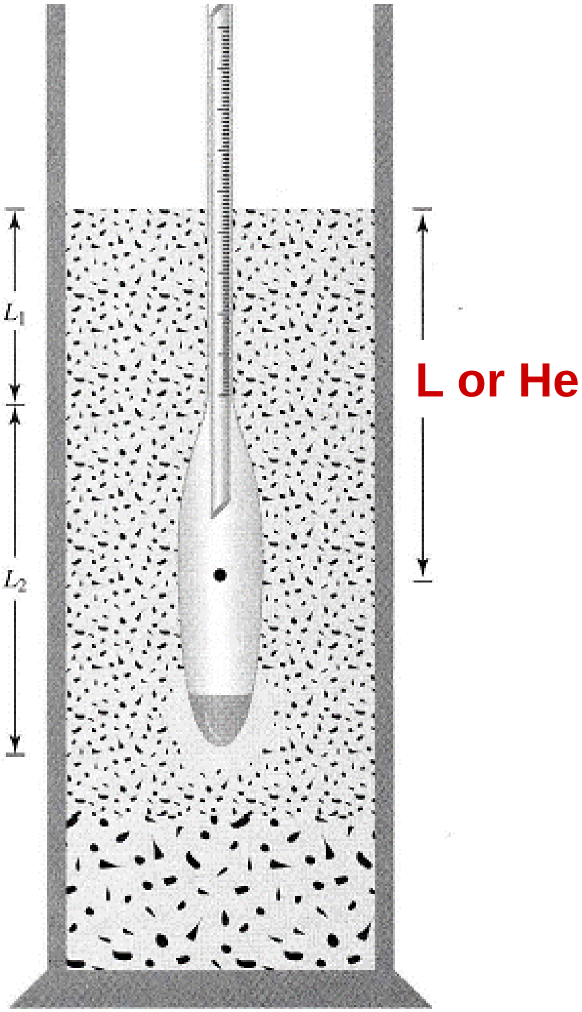
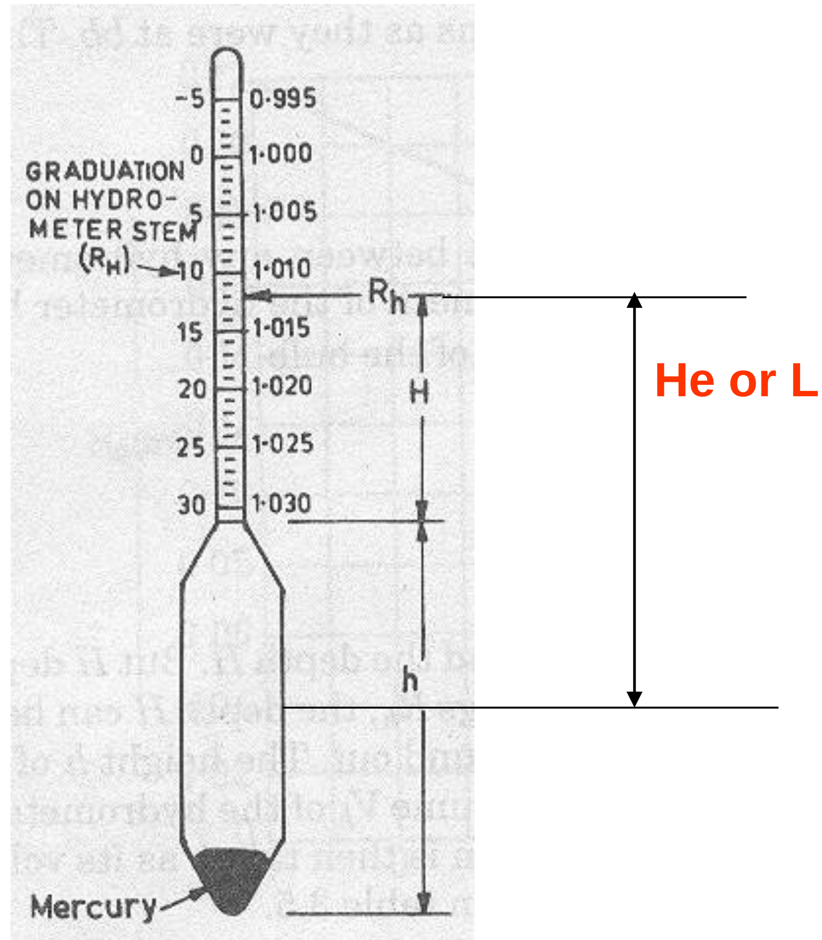
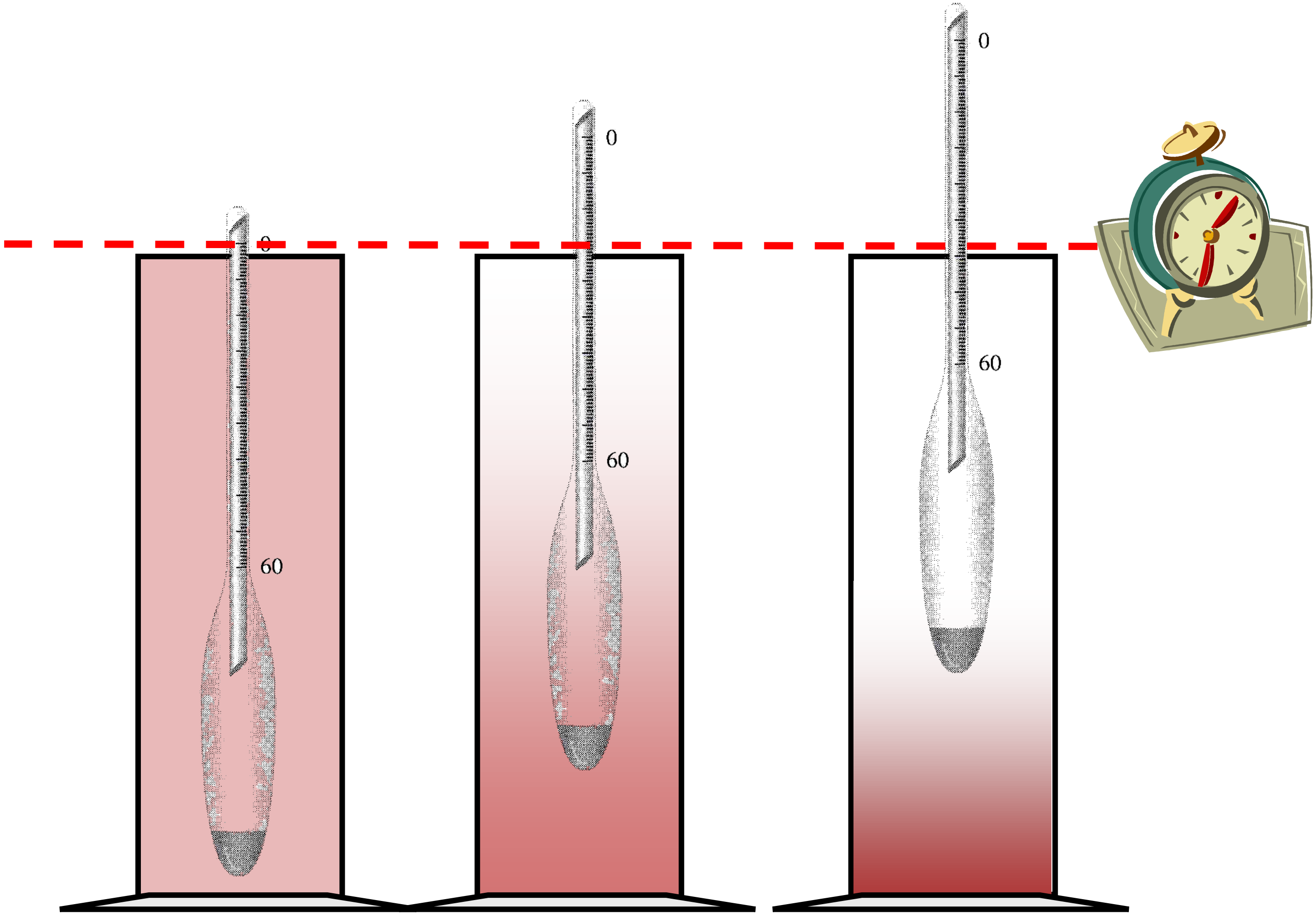


Figure 2.17 Definition of L in hydrometer test



$$\rho = \left[1 + \frac{R_h}{1000} \right]$$

Hydrometer Analysis



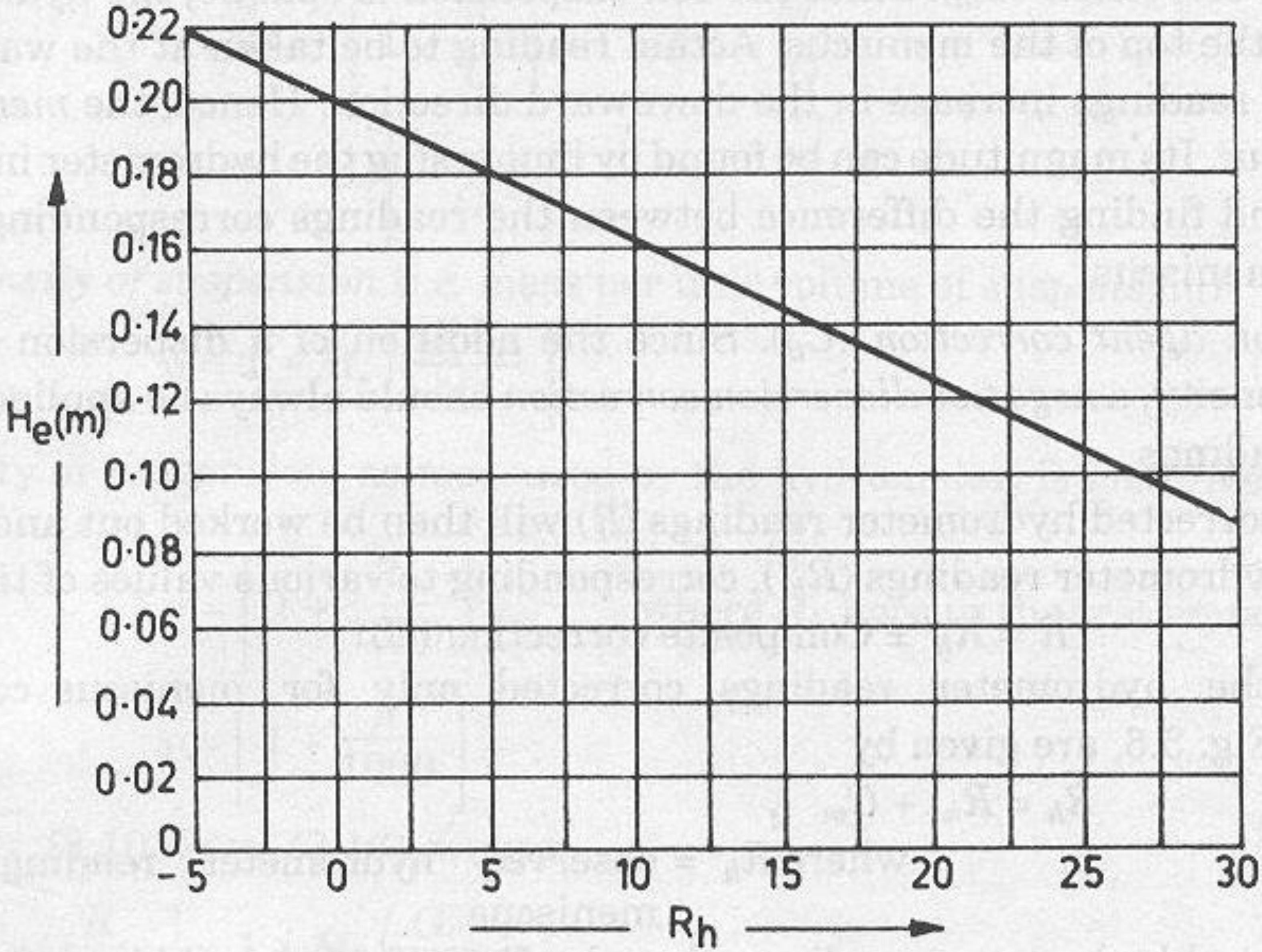


Fig. 3.6. Calibration curve of the given hydrometer and jar.

Hydrometer Analysis

Stokes' Law

$$v = \frac{\rho_s - \rho_w}{18\,\eta} D^2$$

$$D = \sqrt{\frac{L}{t}}\sqrt{\frac{18\,\eta}{\rho_s - \rho_w}}$$

$$D = K\sqrt{\frac{L}{t}}$$

Hydrometer Analysis

Table 2.6 Values of K from Eq. (2.6)[a]

Temperature (°C)	G_s							
	2.45	2.50	2.55	2.60	2.65	2.70	2.75	2.80
16	0.01510	0.01505	0.01481	0.01457	0.01435	0.01414	0.01394	0.01374
17	0.01511	0.01486	0.01462	0.01439	0.01417	0.01396	0.01376	0.01356
18	0.01492	0.01467	0.01443	0.01421	0.01399	0.01378	0.01359	0.01339
19	0.01474	0.01449	0.01425	0.01403	0.01382	0.01361	0.01342	0.01323
20	0.01456	0.01431	0.01408	0.01386	0.01365	0.01344	0.01325	0.01307
21	0.01438	0.01414	0.01391	0.01369	0.01348	0.01328	0.01309	0.01291
22	0.01421	0.01397	0.01374	0.01353	0.01332	0.01312	0.01294	0.01276
23	0.01404	0.01381	0.01358	0.01337	0.01317	0.01297	0.01279	0.01261
24	0.01388	0.01365	0.01342	0.01321	0.01301	0.01282	0.01264	0.01246
25	0.01372	0.01349	0.01327	0.01306	0.01286	0.01267	0.01249	0.01232
26	0.01357	0.01334	0.01312	0.01291	0.01272	0.01253	0.01235	0.01218
27	0.01342	0.01319	0.01297	0.01277	0.01258	0.01239	0.01221	0.01204
28	0.01327	0.01304	0.01283	0.01264	0.01244	0.01225	0.01208	0.01191
29	0.01312	0.01290	0.01269	0.01249	0.01230	0.01212	0.01195	0.01178
30	0.01298	0.01276	0.01256	0.01236	0.01217	0.01199	0.01182	0.01169

[a] After ASTM (1999)

$$M_s = \frac{R}{1000}\left(\frac{G}{G-1}\right)$$

$$P = \left[\frac{\frac{R}{1000}\left(\frac{G}{G-1}\right)}{\frac{M}{V}}\right] \times 100$$

Note: Density of water is taken as 1 g/cc

Corrections: Hydrometer Analysis

1. Temperature Correction (C_t)
2. Meniscus Correction (C_m)
3. Dispersing Agent Correction (C_d)

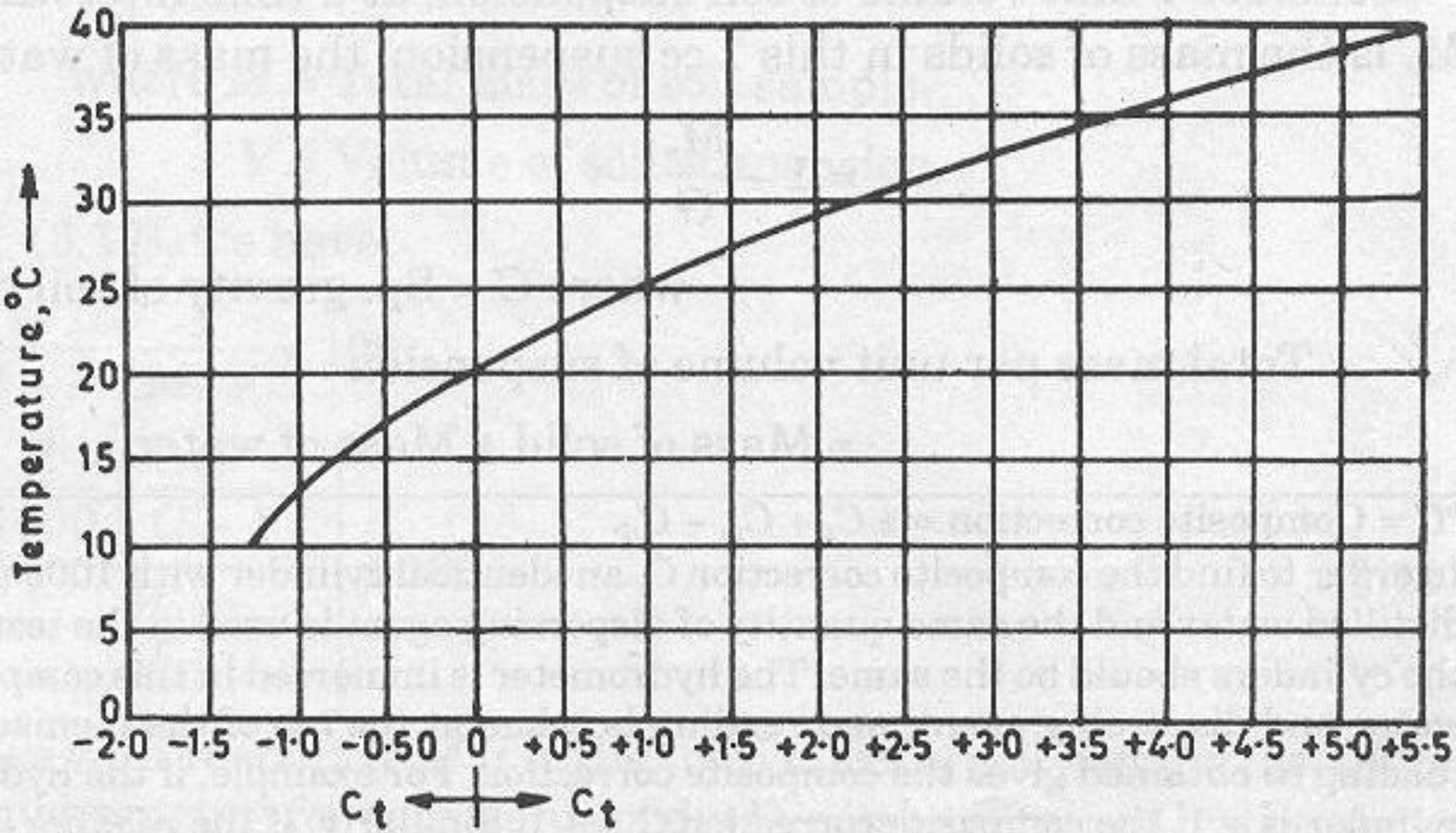


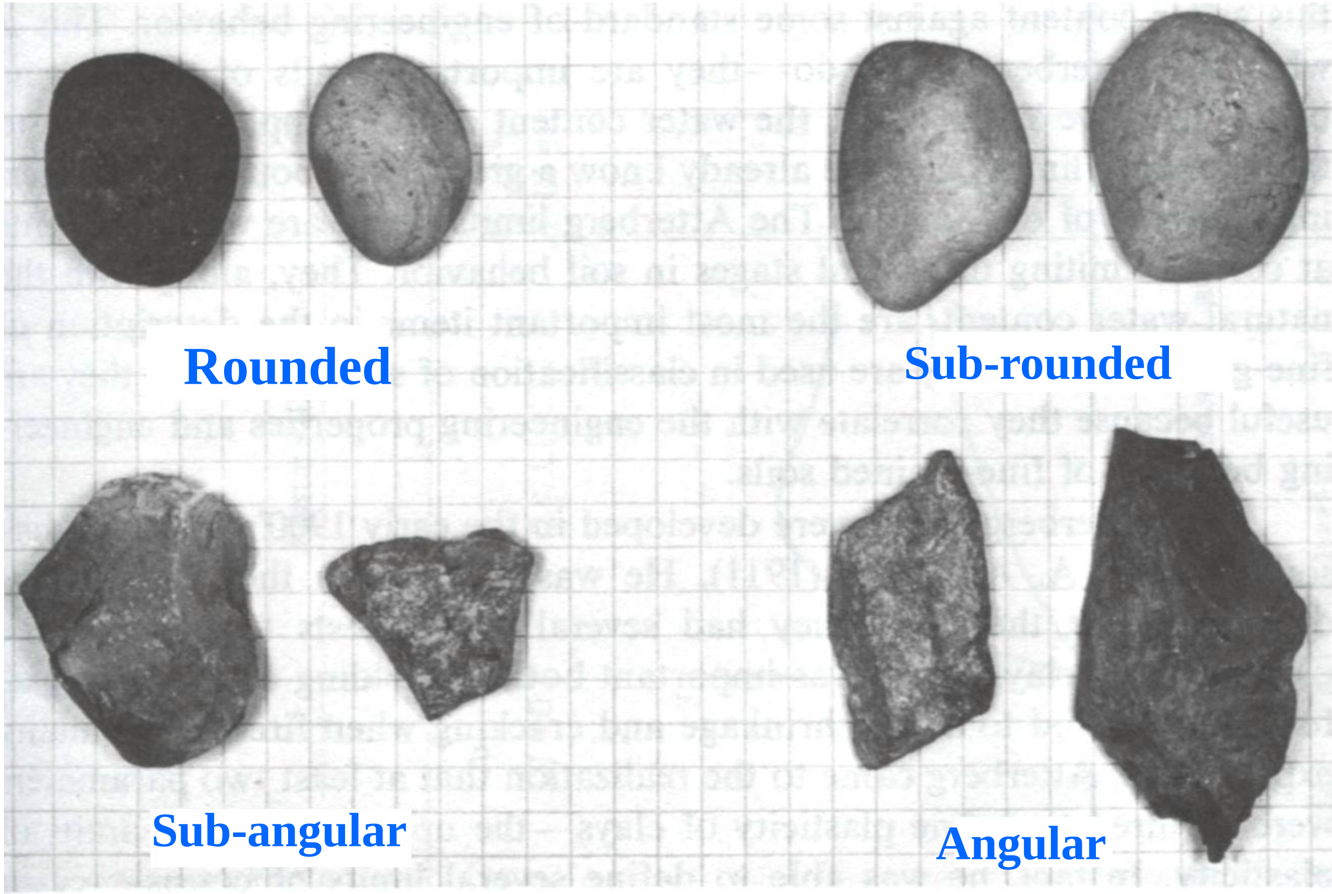
Fig. 3.7. Temperature correction chart for hydrometers calibrated at 20°C.

$$R = R_h \pm C_t + C_m - C_d$$

1. **R=Corrected Hydrometer Reading**
2. **R_h=Observed Hydrometer Reading**
3. **C_t= Temperature Correction**
4. **C_m= Meniscus Correction**
5. **C_d=Dispersing Agent Correction**

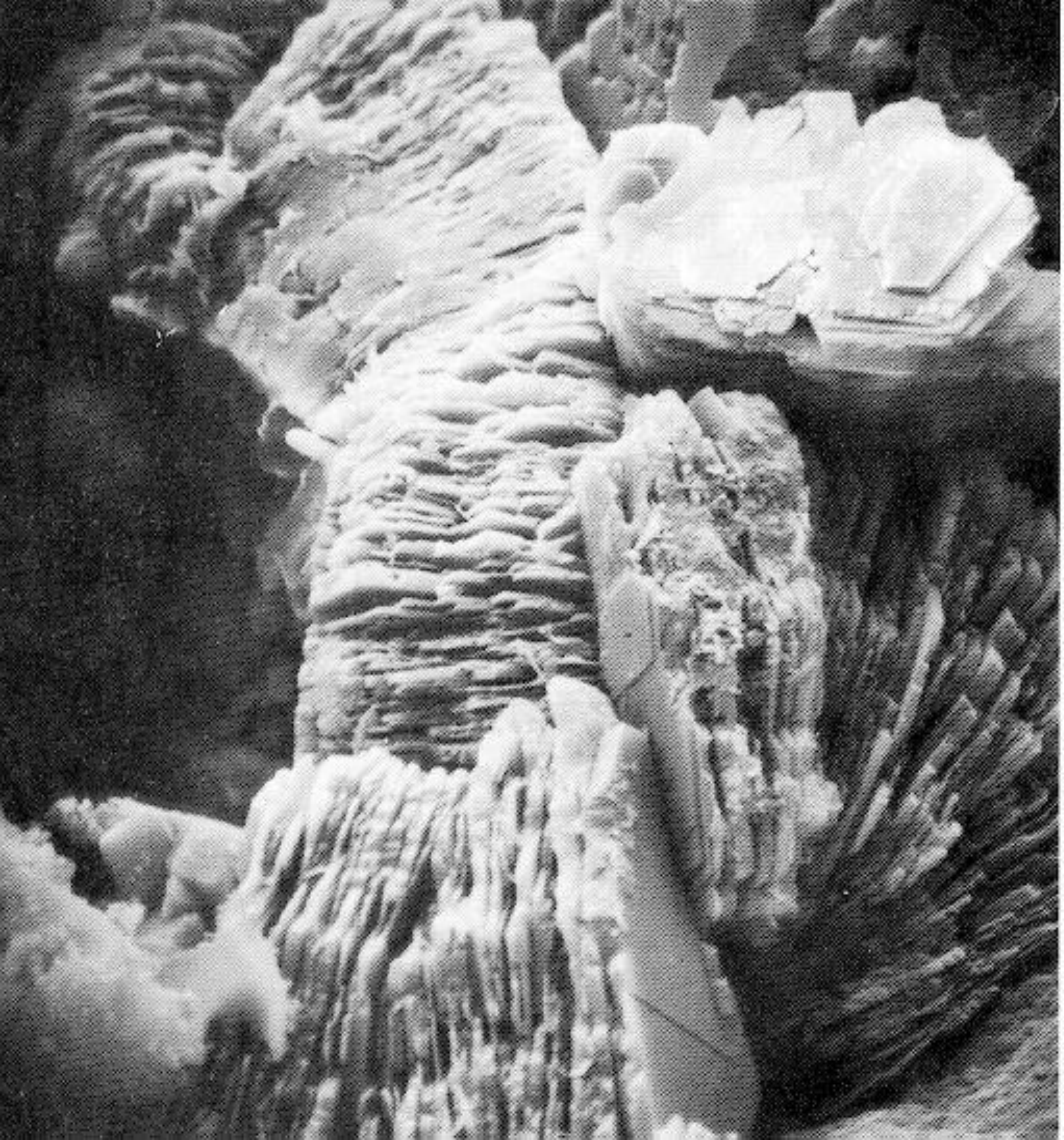
4. Particle Shape

Coarse-grained soils



–Important for granular soils

- Angular soil particle → higher friction
- Round soil particle → lower friction
- Note that clay particles are sheet-like.



Clay minerals photographed with an electron Microscope.

Note: they are plate or flake like and are stacked on top of each other.

They are electrically charged and act like magnets

5. Soil Consistency and Atterberg Limits

Soil Consistency

Soil consistence provides a means of describing the degree and kind of cohesion and adhesion between the soil particles as related to the resistance of the soil to deform or rupture

Soil Behave Like:

- **SOILD at very low moisture content**
- **LIQUID at very high moisture content**

- The presence of water in fine-grained soils can significantly affect associated engineering behavior, so we need a reference index to clarify the effects.

Atterberg Limits
and
Consistency Indices

Soil Consistency - Atterberg Limits

Depending on Moisture Content soil can be divided into:

Moisture Content (w)

\-

1. **Solid State** **(Atterberg Limits)**

Shrinkage Limit (SL)

2. **Semi-Solid State**

Plastic Limit (PL)

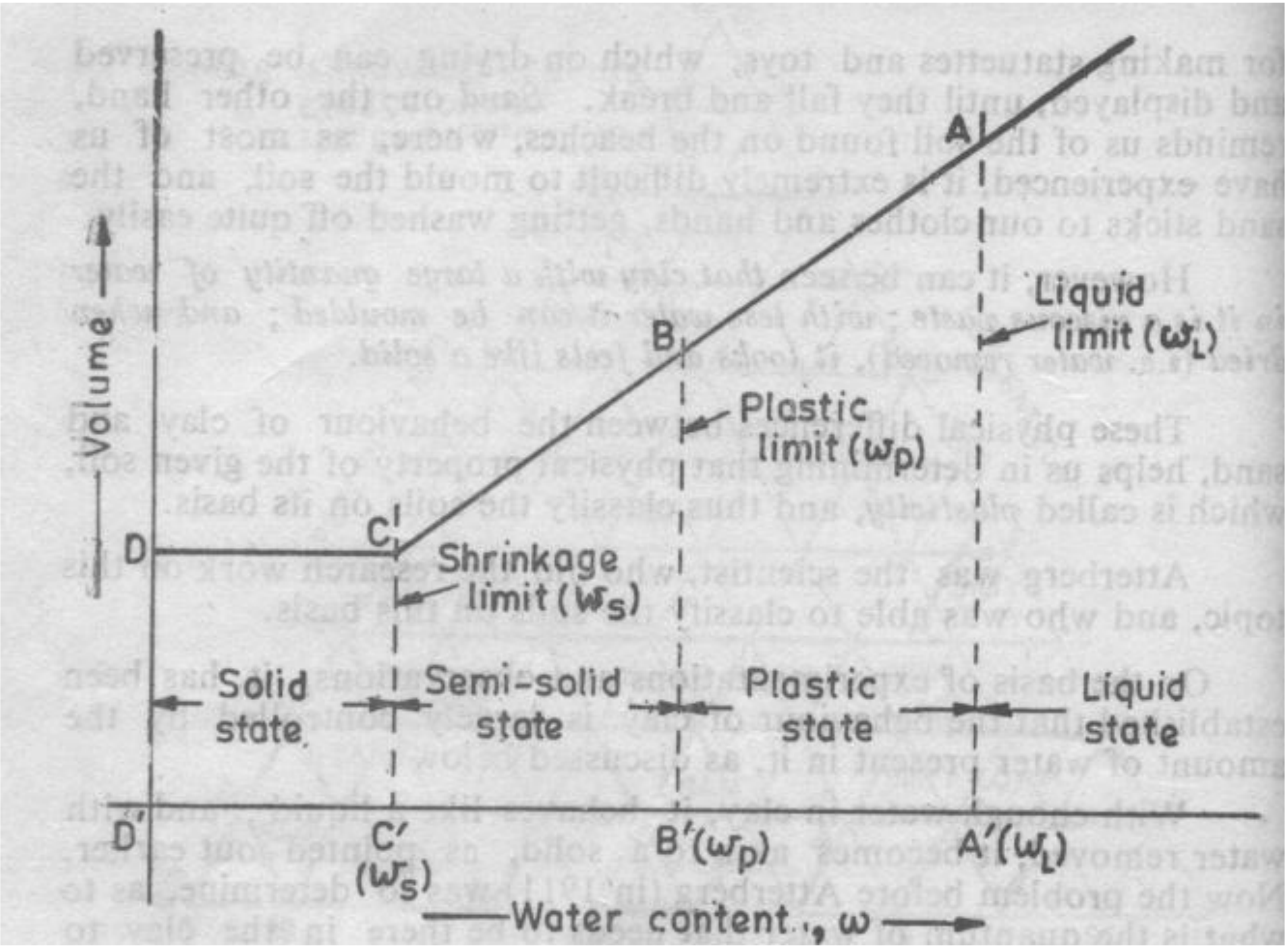
3. **Plastic State**

Liquid Limit (LL)

4. **Liquid State**

\+

Different states of soil at different water contents



The Atterberg limits are based on the moisture content of the soil.

The liquid limit: is the moisture content that defines where the soil changes from a plastic to a viscous fluid state.

The plastic limit: is the moisture content that defines where the soil changes from a semi-solid to a plastic (flexible) state.

The shrinkage limit: is the moisture content that defines where the soil changes from a semi solid state to solid state and at which the soil volume ceases to change.

Atterberg Limits

Liquid Limit (w_L or LL):

Clay flows like liquid when $w > LL$

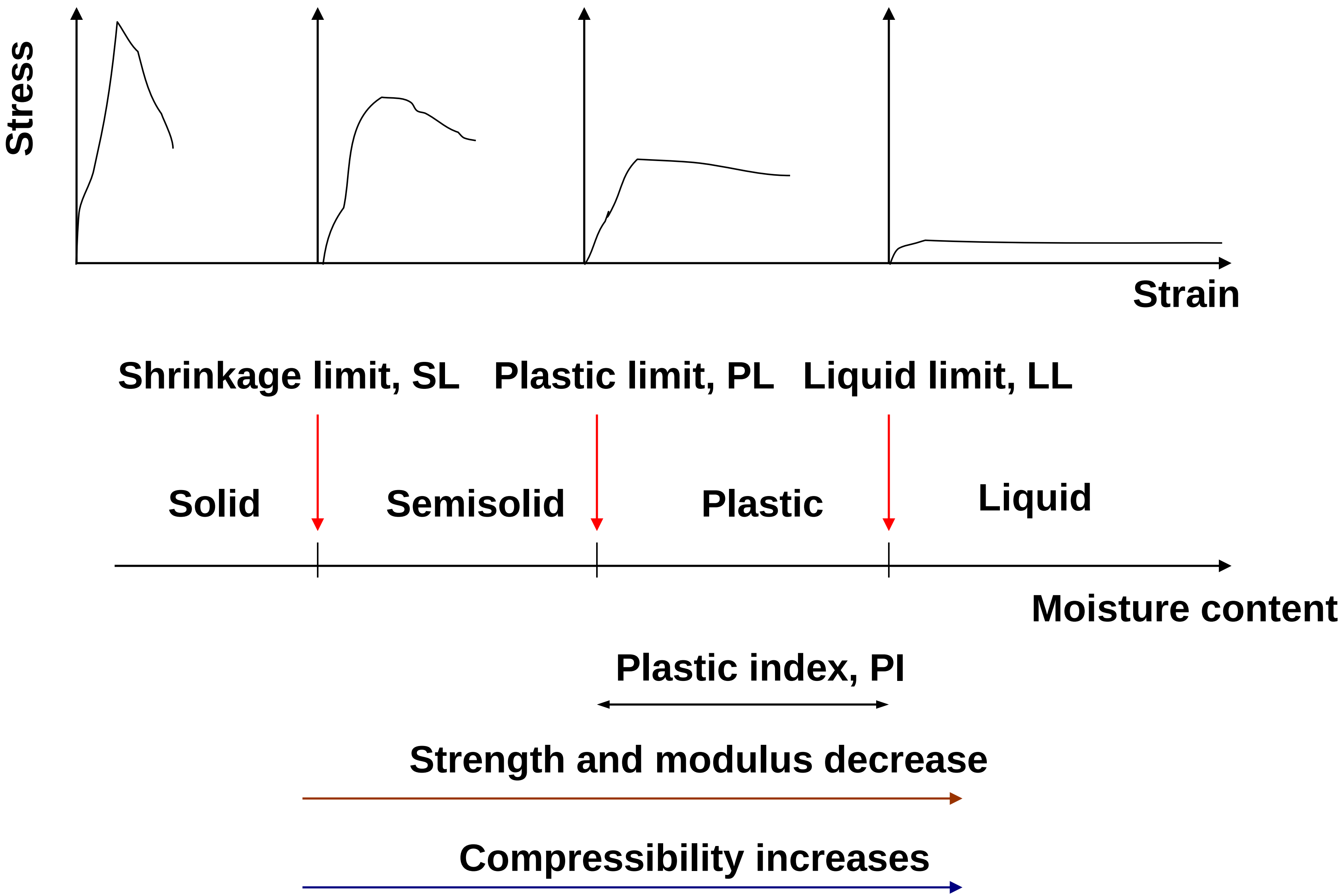
Plastic Limit (w_P or PL):

Lowest water content where the clay is still plastic

Shrinkage Limit (w_S or SL):

At $w<SL$, no volume reduction on drying

Consistency of Soil - Atterberg Limits



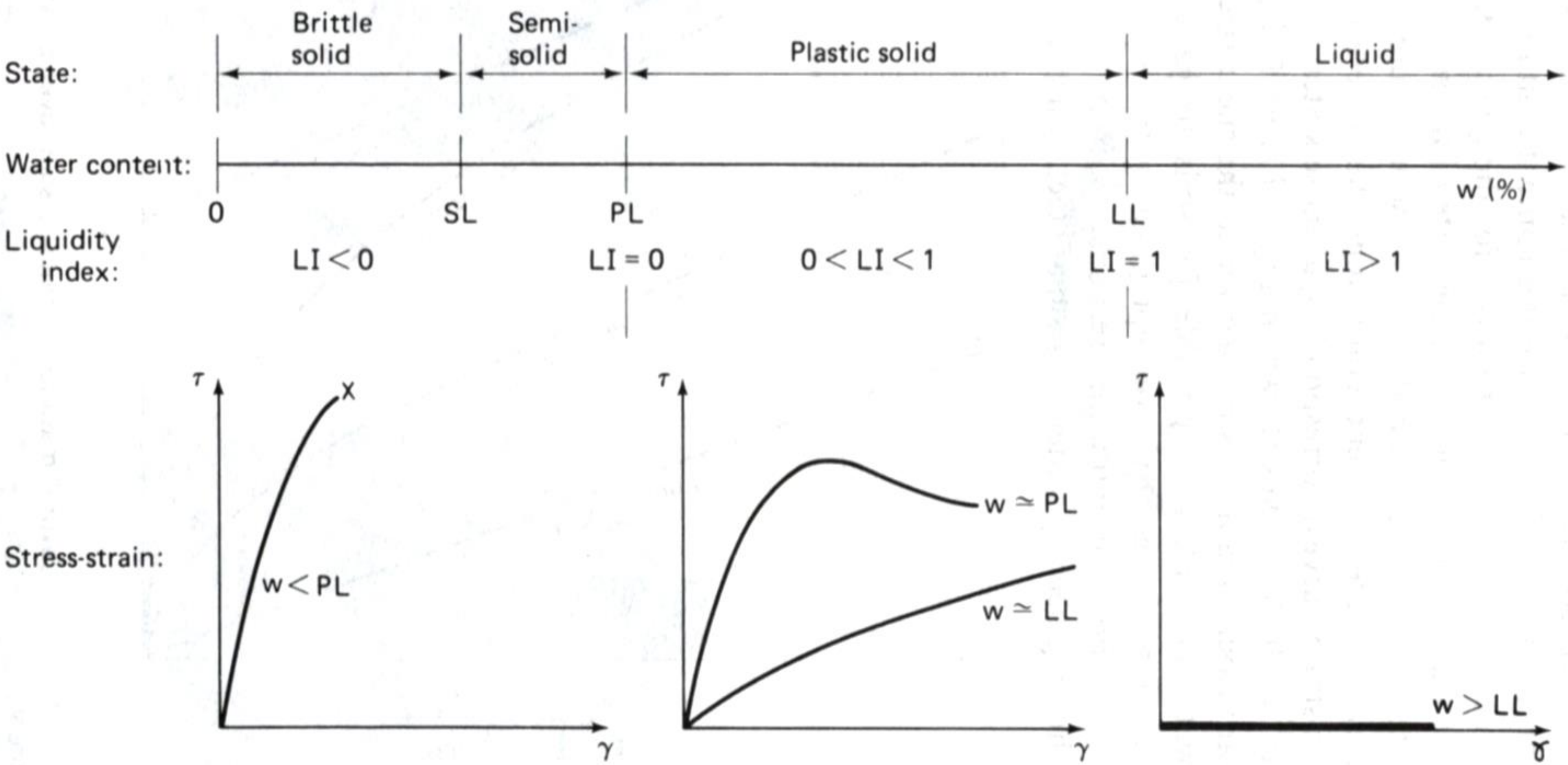
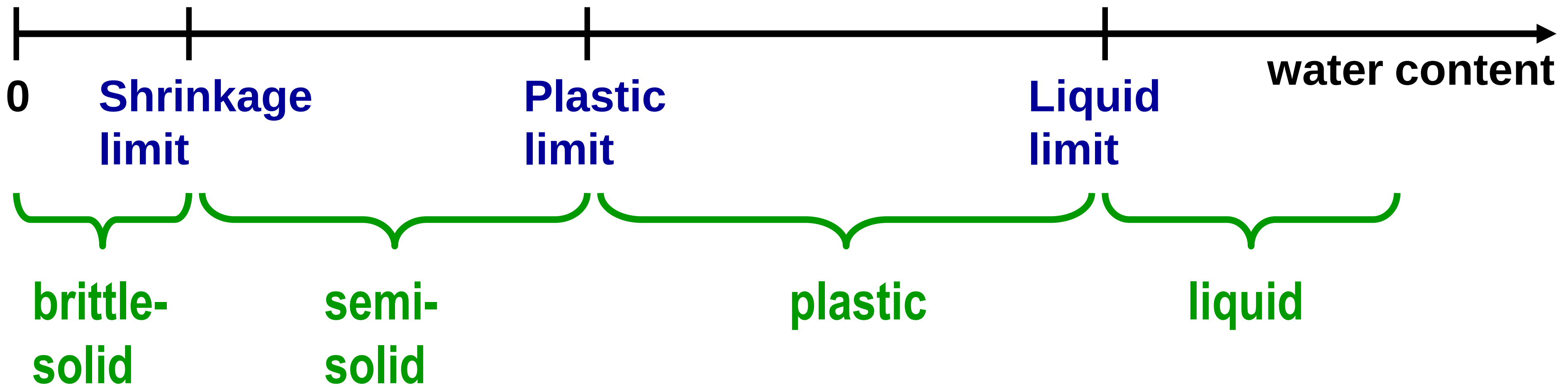


Fig. 2.6 **Water content continuum showing the various states of a soil as well as the generalized stress-strain response.**

(Holtz and Kovacs, 1981)

Atterberg Limits

- Border line **water contents**, separating the different **states** of a fine grained soil



Determination of Atterberg Limits

Lab Tests are performed to determine the liquid, plastic and shrinkage limits of a fine grained soil.

Liquid Limit (LL or w_L)

- **Casagrande Method**
- (ASTM D4318-95a)
- Professor Casagrande standardized the test and developed the liquid limit device.
- Multipoint test
- One-point test

- **Cone Penetrometer Method**
- (BS 1377: Part 2: 1990:4.3)
- This method is developed by the Transport and Road Research Laboratory, UK.
- Multipoint test
- One-point test

Liquid Limit Definition

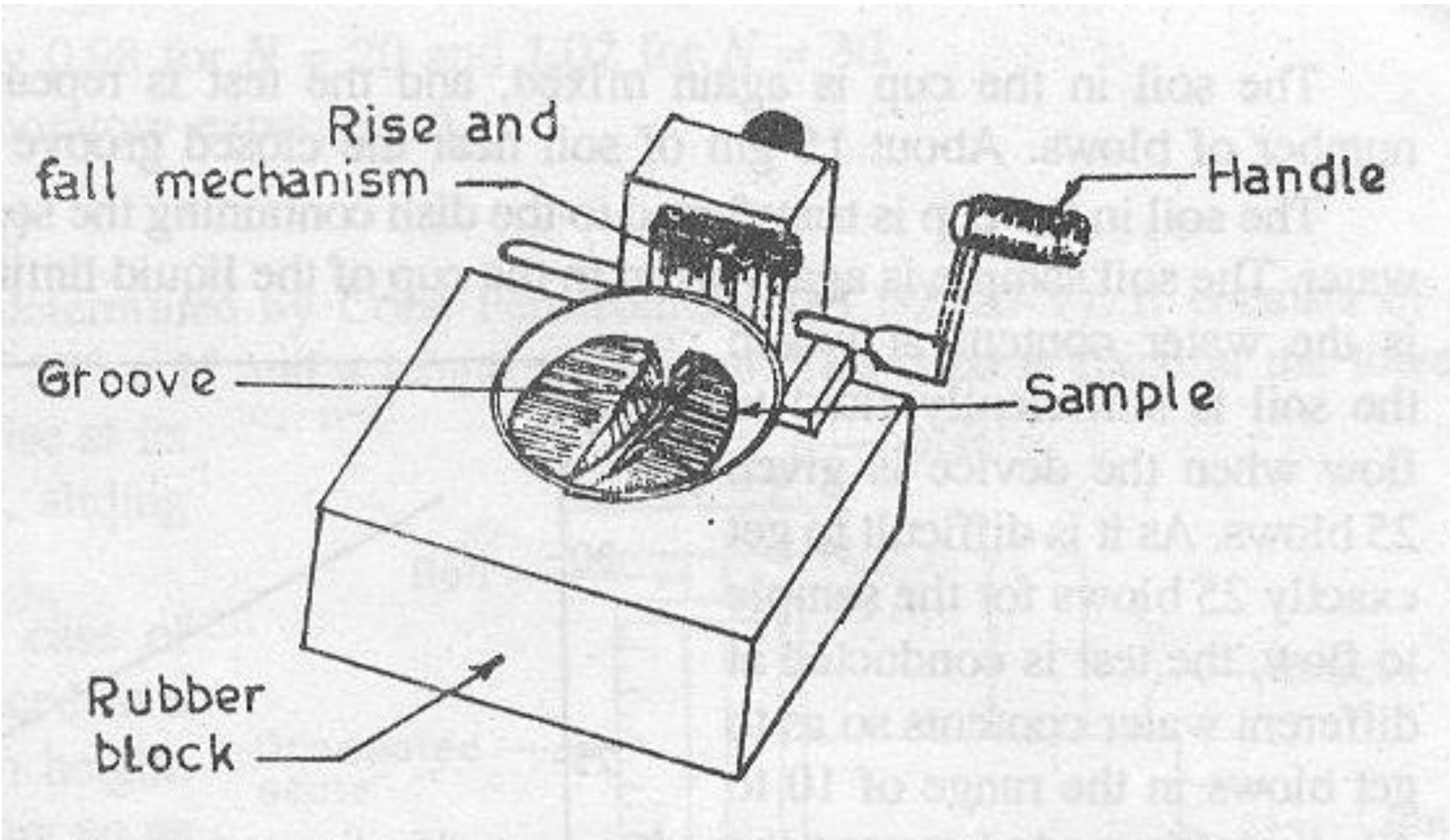
- The water content at which a soil changes from a plastic consistency to a liquid consistency
- Defined by Laboratory Test concept developed by Atterberg in 1911.

Liquid Limit-LL (Cont.)

- **Dynamic shear test**
- Shear strength is about 1.7 ~2.0 kPa.
- Pore water suction is about 6.0 kPa.
  - (review by Head, 1992; Mitchell, 1993).

- **Particle sizes and water**
- Passing No.40 Sieve (0.425 mm).
- Using deionized water.

  The type and amount of cations can significantly affect the measured results.


Rise and
fall mechanism
Handle
Groove
Sample
Rubber
block

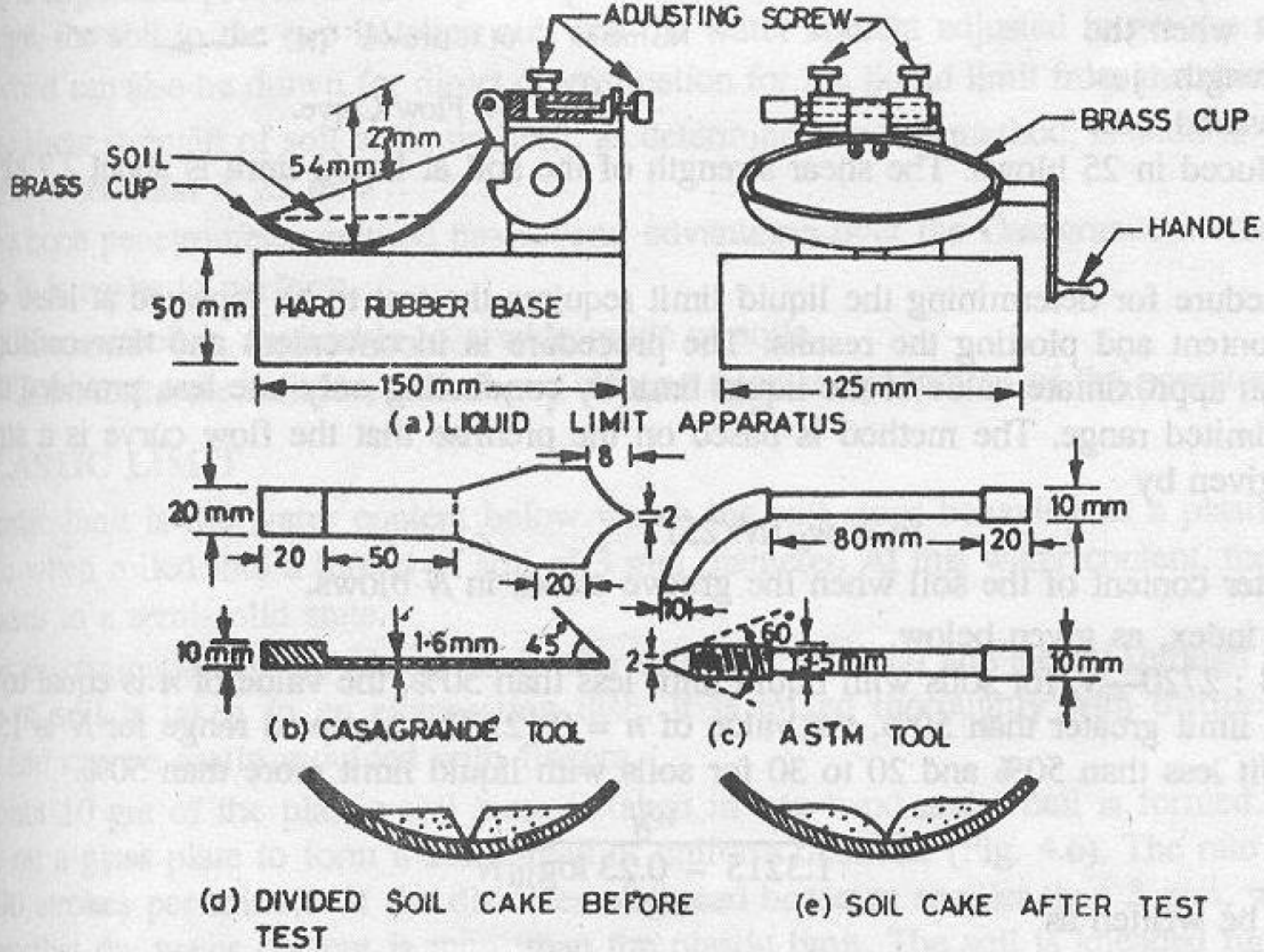


Fig. 4.3. Details of Apparatus and Tools.

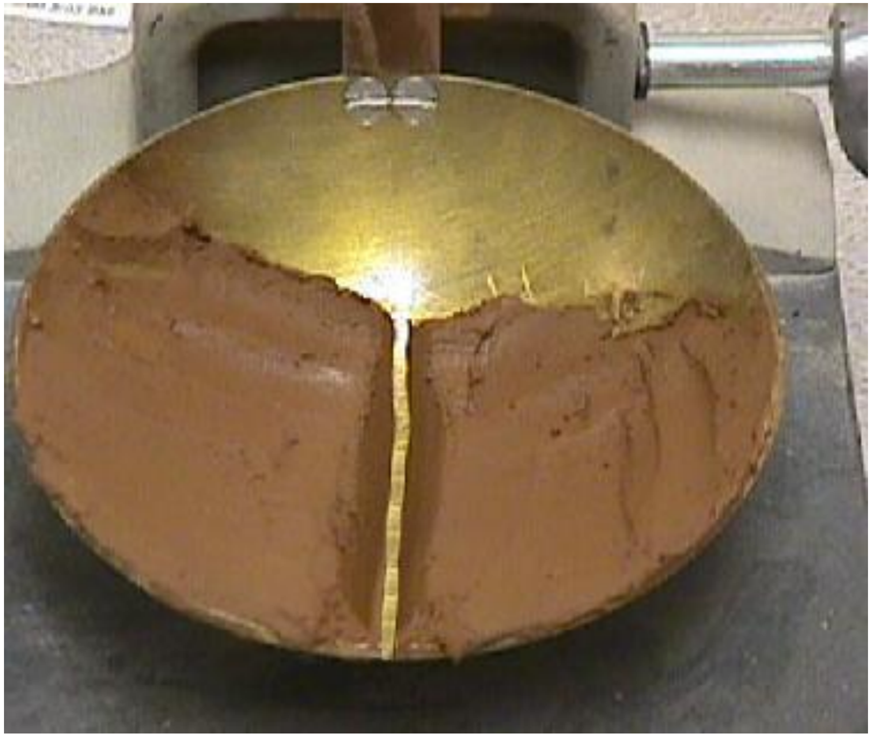

A
Spatula
Liquid limit device
Grooving
tool
Soil specimen
Moisture cans

LL Test Procedure

- Prepare paste of soil finer than 425 micron sieve
- Place Soil in Cup

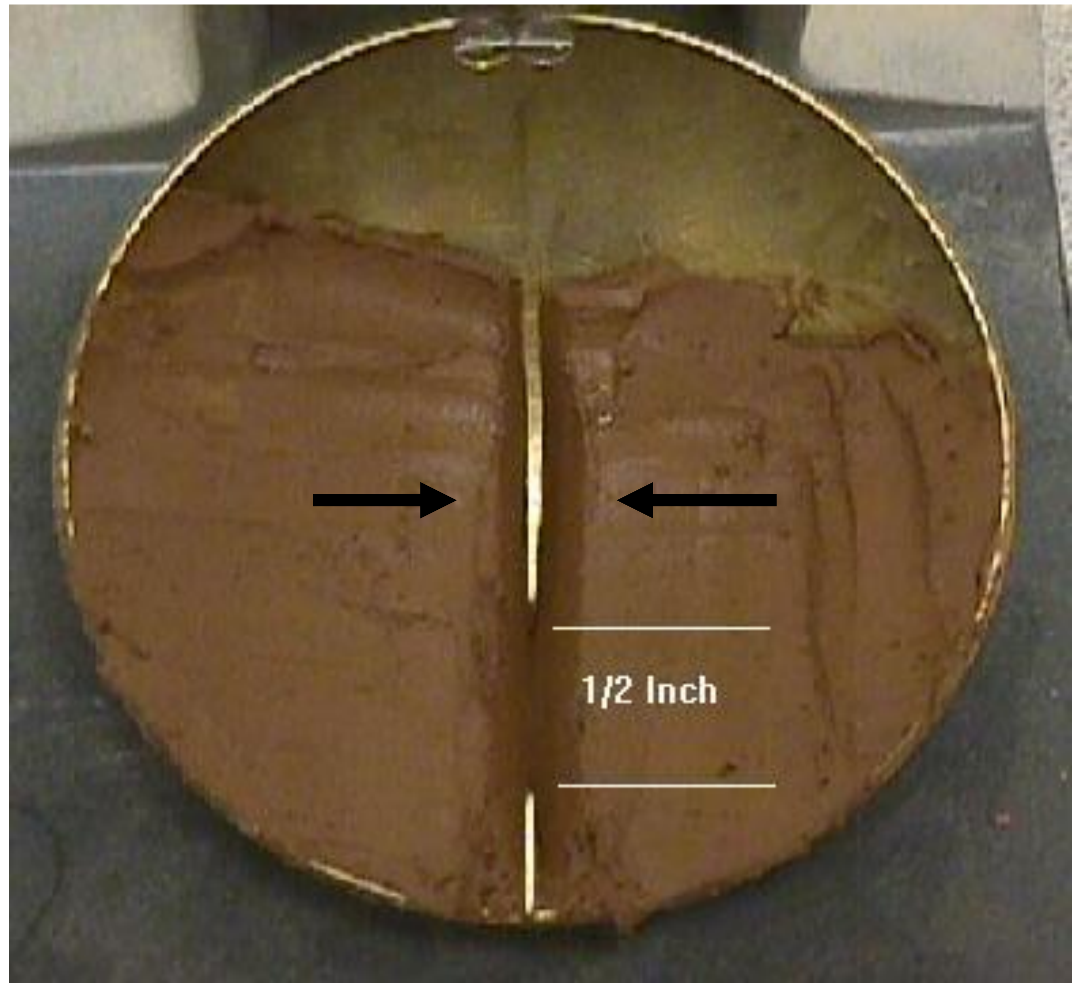
LL Test Procedure

- Cut groove in soil paste with standard grooving tool



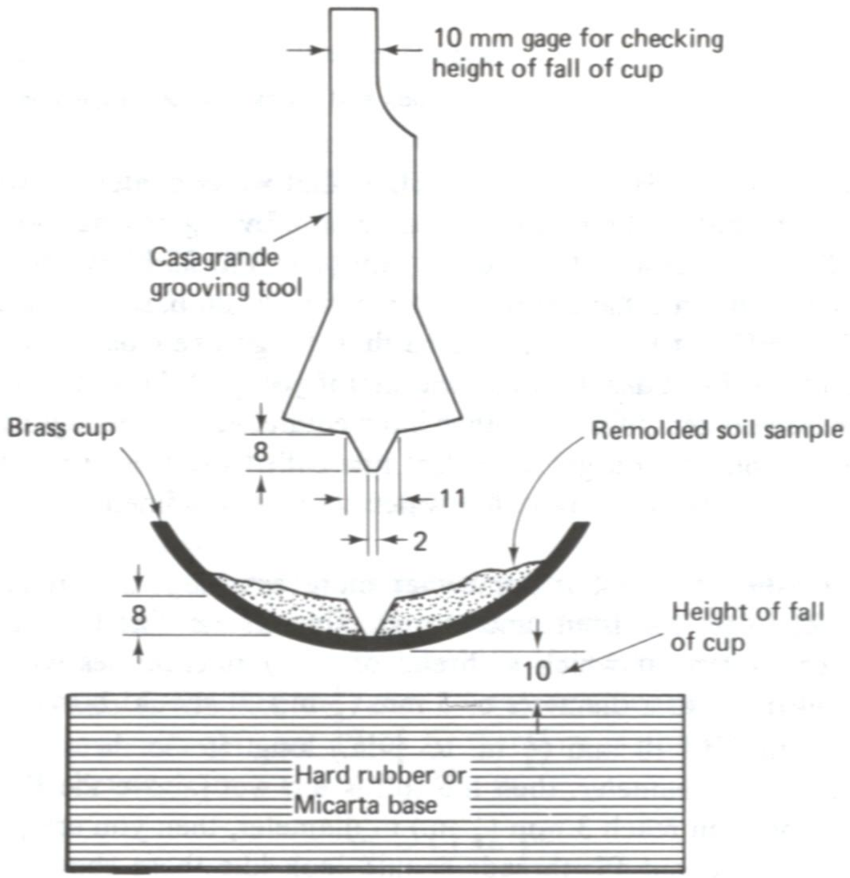
LL Test Procedure

- Rotate cam and count number of blows of cup required to close groove by 1/2”

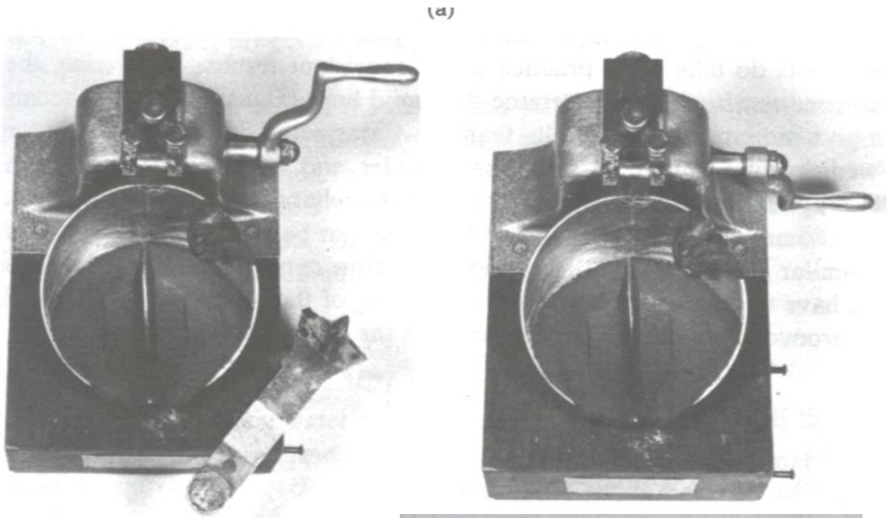


Casagrande Method

- **Device**

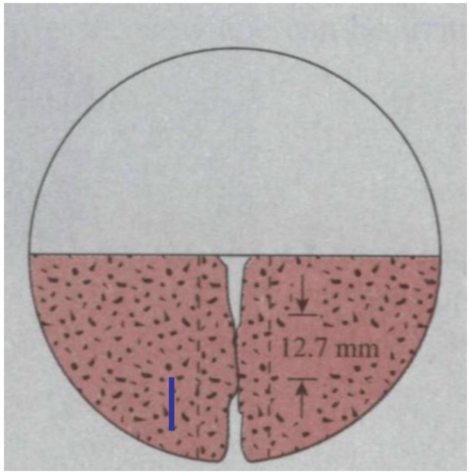


(Holtz and Kovacs, 1981)



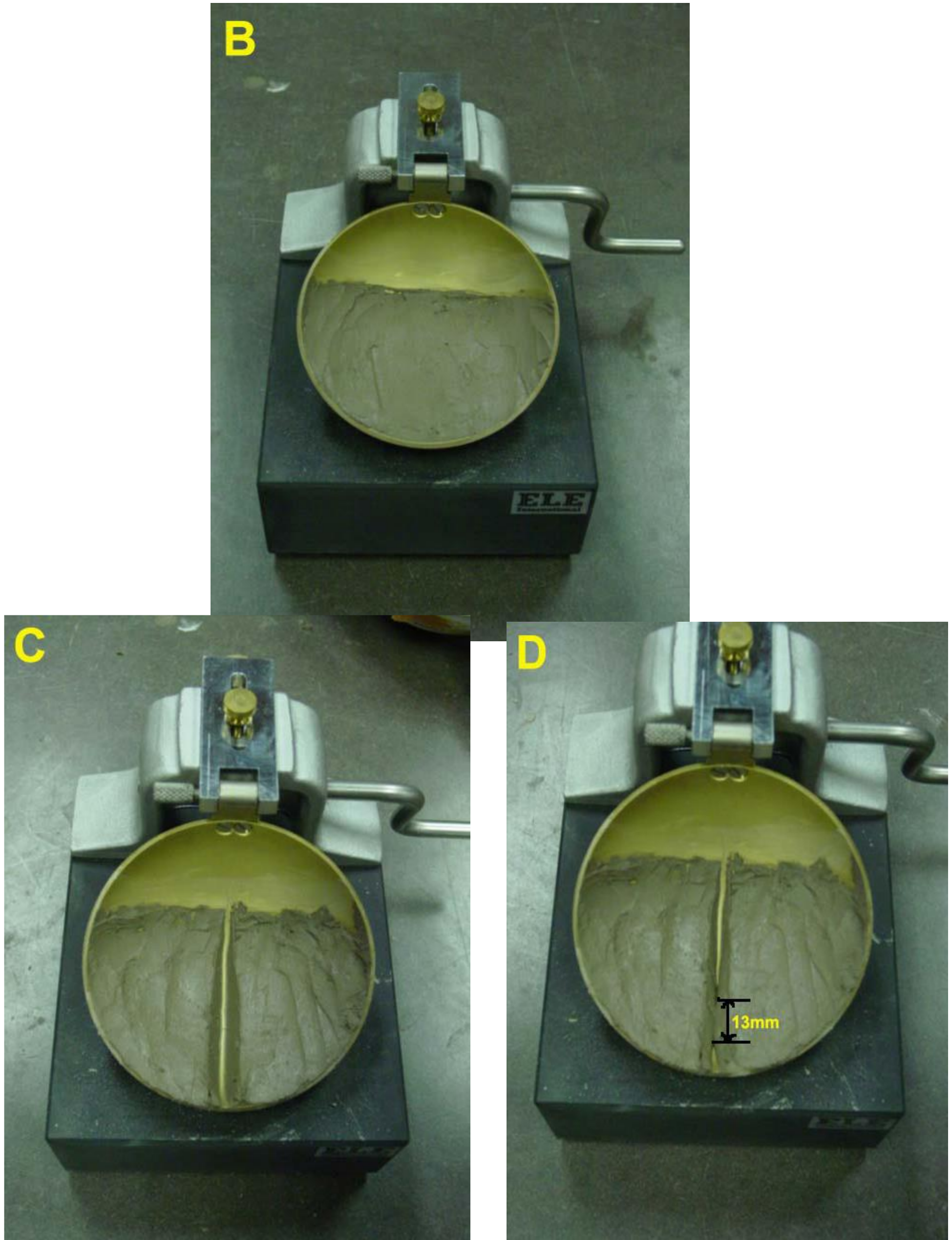
N=25 blows

Closing distance = 12.7mm (0.5 in)



The water content, in percentage, required to close a distance of 0.5 in (12.7mm) along the bottom of the groove after 25 blows is defined as the liquid limit

● **Defined by Laboratory Test concept developed by Atterberg in 1911.**



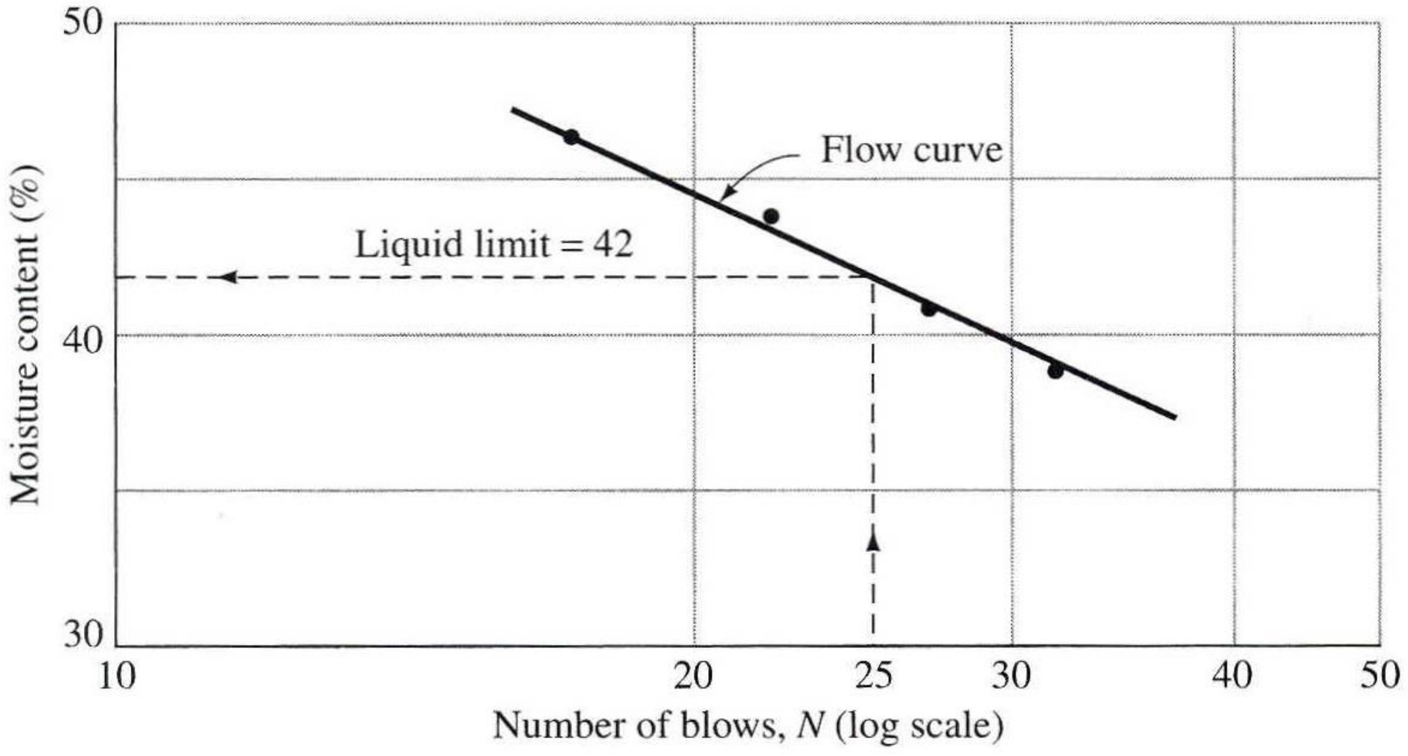
The liquid limit (LL) is arbitrarily defined as the water content, in percent, at which a pat of soil in a standard cup and cut by a groove of standard dimensions will flow together at the base of the groove for a distance of 12 mm under the impact of 25 blows in the devise.

The cup being dropped 10 mm in a standard liquid limit apparatus operated at a rate of two shocks per second.

LL Test Procedure

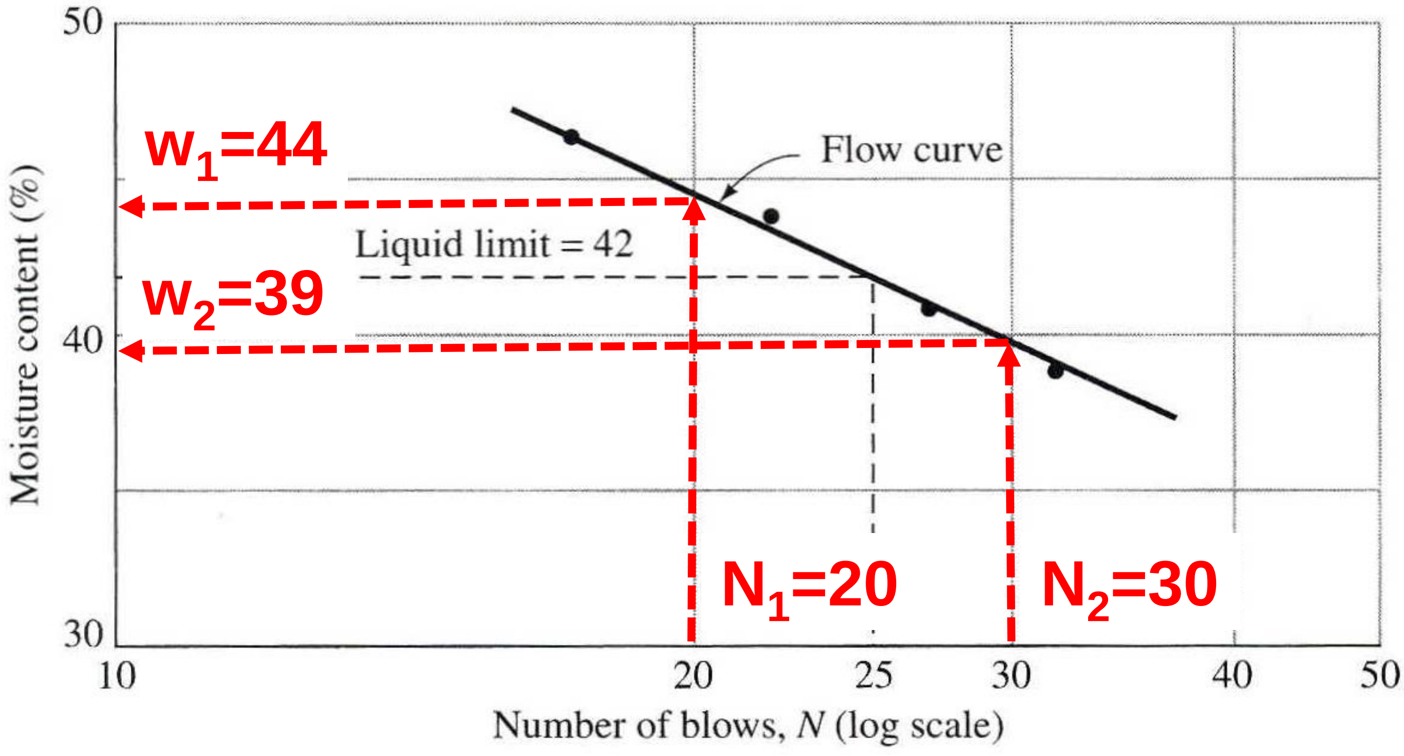
- Perform on 3 to 4 specimens that bracket 25 blows to close groove
- Obtain water content for each test
- Plot water content versus number of blows on semi-log paper

Liquid Limit - Measurement



Liquid Limit (LL) at N = 25

Liquid Limit – Flow Index



$$Flow\ index, I_F = \frac{w_1 - w_2}{\log\left(N_2 / N_1\right)} (choose\ a\ \ positive\ value)$$

One point Method

$$w_l = w_N (N/25)^n$$

For soils having liquid limit less than 50%

n will b 0.92 N will be 15 to 35

For soils having liquid limit greater than 50%

n will b 0.121, N will be 20 to 30

Cone Penetrometer Method or Fall Cone Method (BS1377)

- **Device**

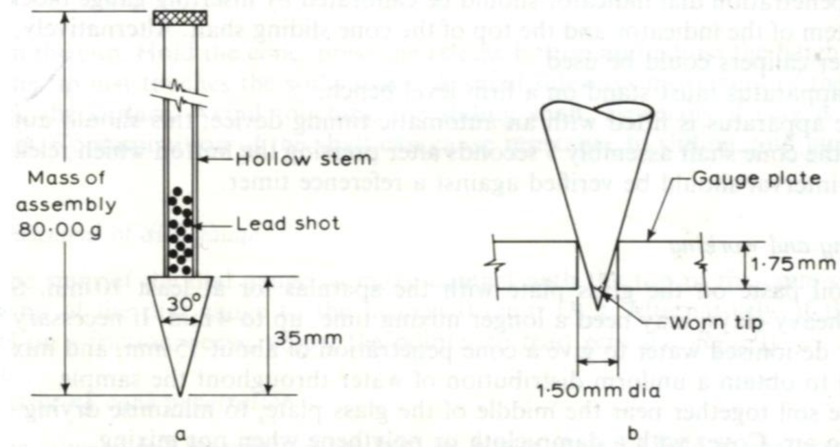
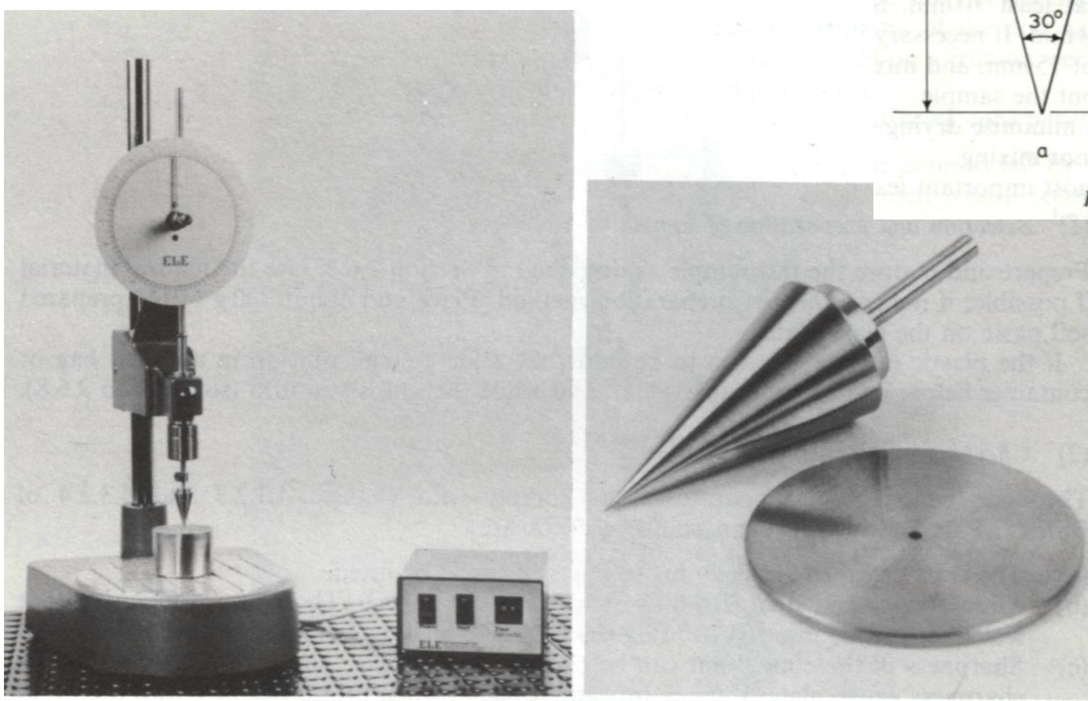


Fig. 2.12 Details of cone for penetrometer



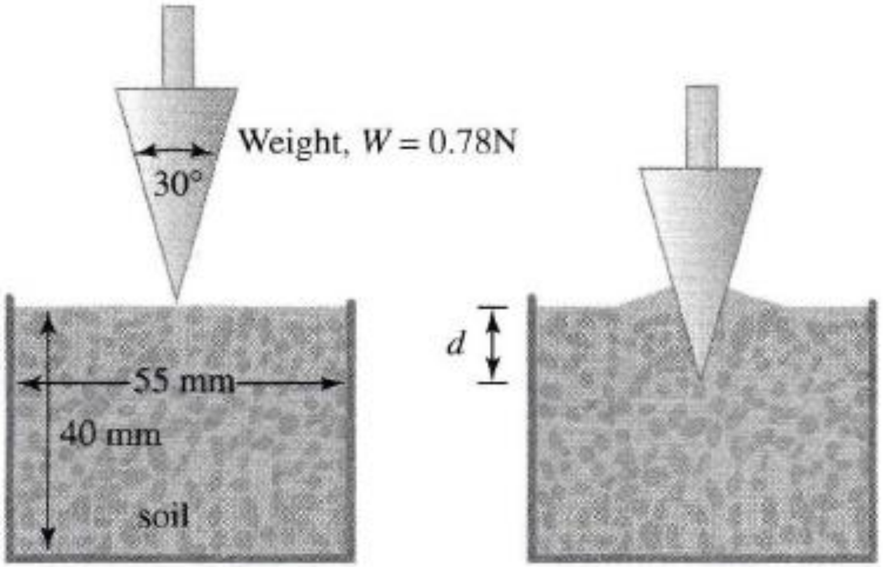
(a) (b)

Fig. 2.11 Apparatus for cone penetrometer liquid test: (a) Cone penetrometer with automatic timing device, (b) cone and gauge plate

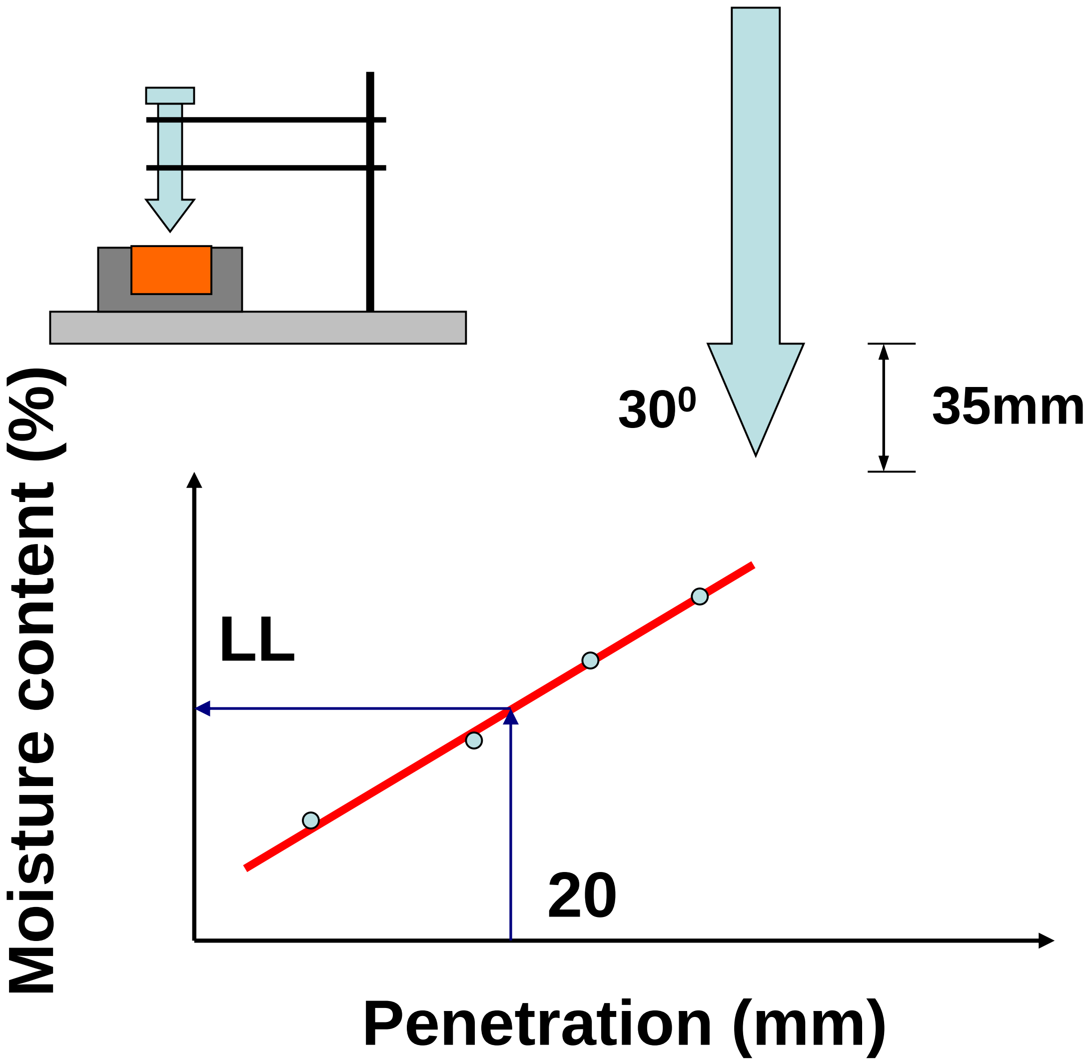
This method is developed by the Transport and Road Research Laboratory.

(Head, 1992)

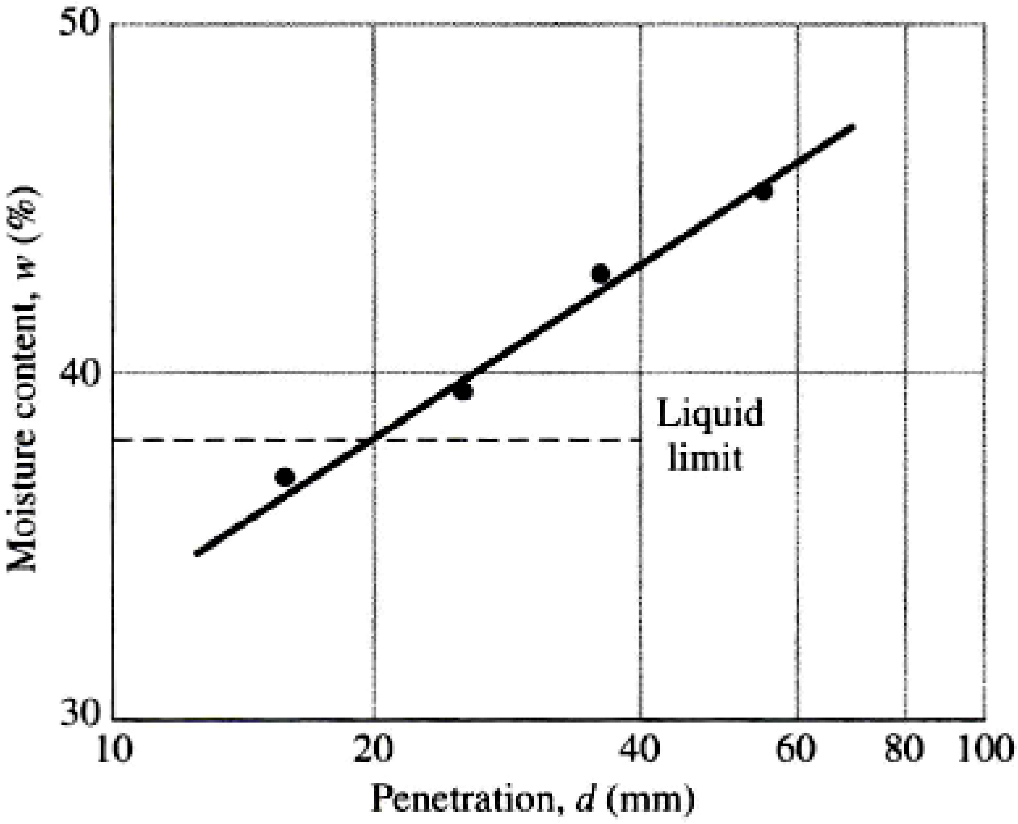
Liquid Limit - Measurement



Liquid Limit Test



Liquid Limit - Measurement



Liquid Limit (LL) at d = 20 mm

$$I_{FC} = \frac{w_2(\%) - w_1(\%)}{\log d_2 - \log d_1}$$

4.2.2 Cone Penetrometer Method (Cont.)

•One-point Method (an empirical relation)

Table 2.5. SUGGESTED FACTORS FOR CONE PENTRATION ONE-POINT LIQUID LIMIT TEST (from Clayton and Jukes, 1978)

Penetration (mm)	*Soil of high plasticity*	*Soil of intermediate plasticity*	*Soil of low plasticity*
15	1.098	→ 1.094	1.057
16	1.075	1.076	1.052
17	1.055	1.058	1.042
18	1.036	1.039	1.030
19	1.018	1.020	1.015
20	1.001	1.001	1.000
21	0.984	0.984	0.984
22	0.967	0.968	0.971
23	0.949	0.954	0.961
24	0.929	0.943	0.955
25	0.909	0.934	0.954
Measured moisture content range	above 50%	→ 35% to 50%	below 35%

(Review by Head, 1992)

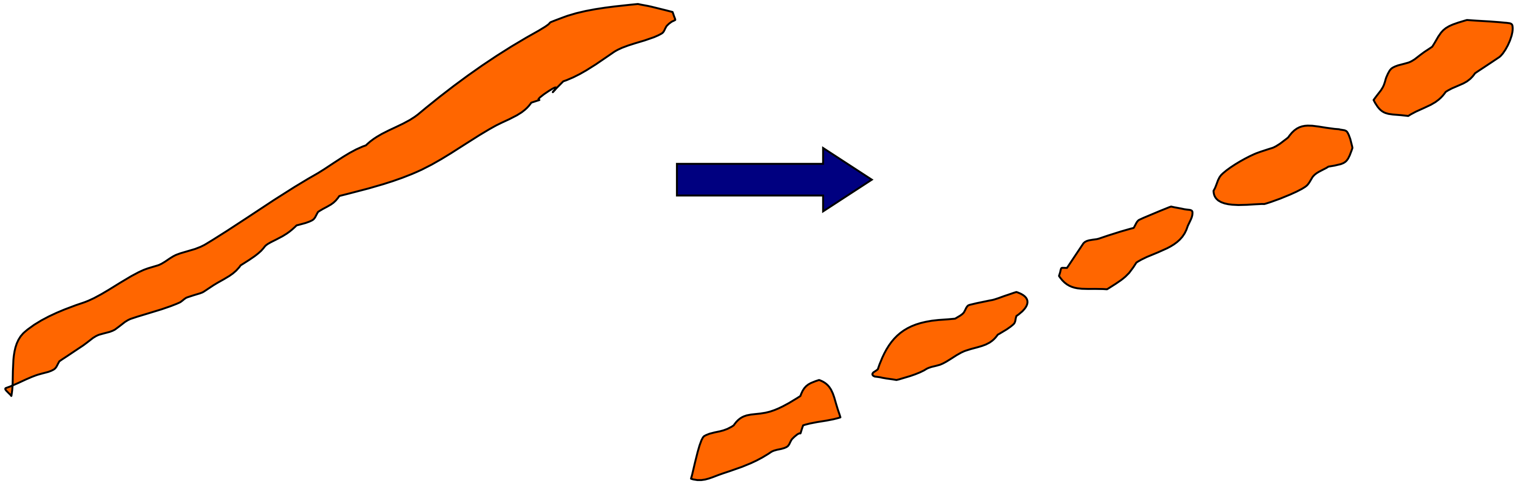
Example: $\text{Penetration depth} = 15\,\text{mm},\ w = 40\%,$

$$\text{Factor} = 1.094,\ LL = 40 \cdot 1.094 \approx 44$$

Question:
Which method will render more consistent results?

Plastic Limit Test

Defined as the moisture content at the soil crumbles when rolled into threads of 1/8 in (3.2mm) in diameter



ASTM D4318-95a, BS1377: Part 2:1990:5.3

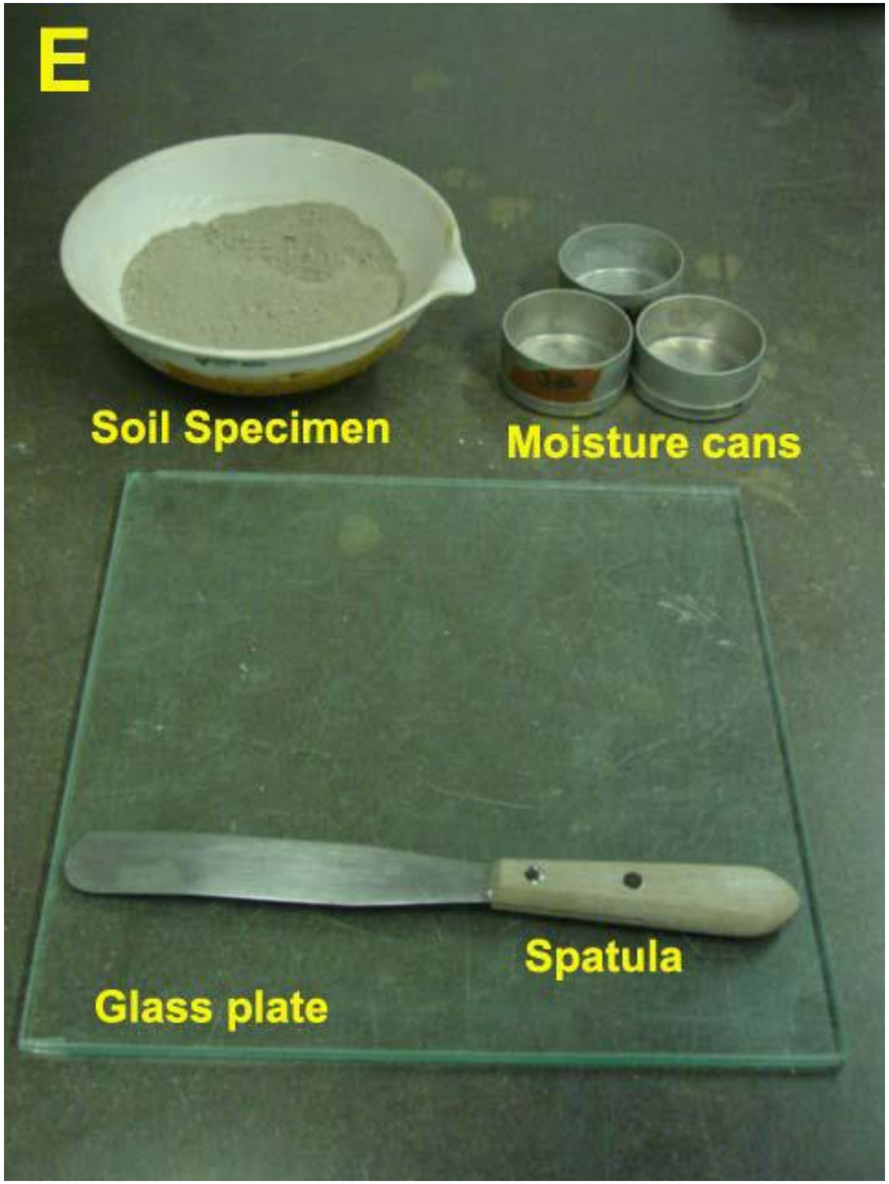
Plastic Limit - Measurement

First Method

ASTM D-4318

PL = w% at d 3.2 mm (1/8 in.)

Plastic Limit



Plastic Limit w% procedure

- Using paste from LL test, begin drying
- May add dry soil or spread on plate and air-dry


F
Ellipsoidal soil mass

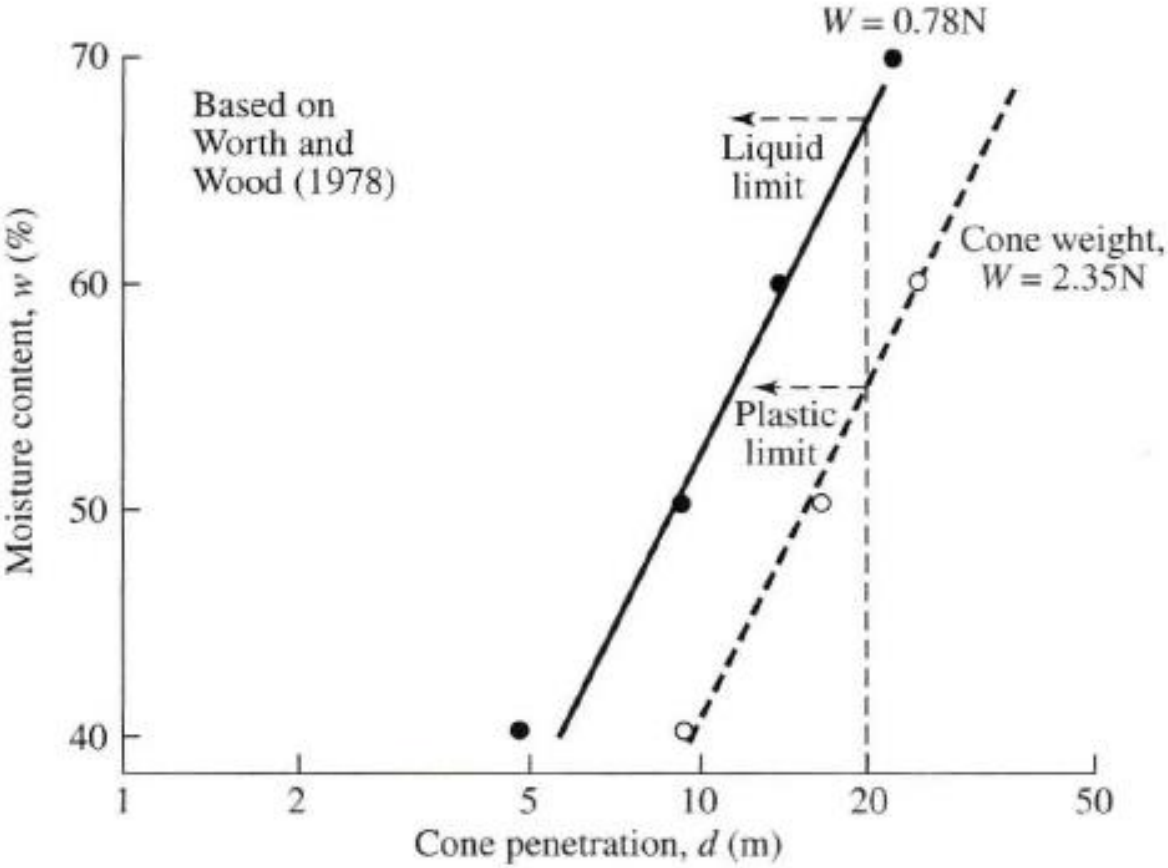

G

1. Calculate the water content of each of the plastic limit moisture cans after they have been in the oven for at least 16 hours.
2. Compute the average of the water contents to determine the plastic limit, PL.

Plastic Limit - Measurement

Second Method

Fall Cone Method BS1377

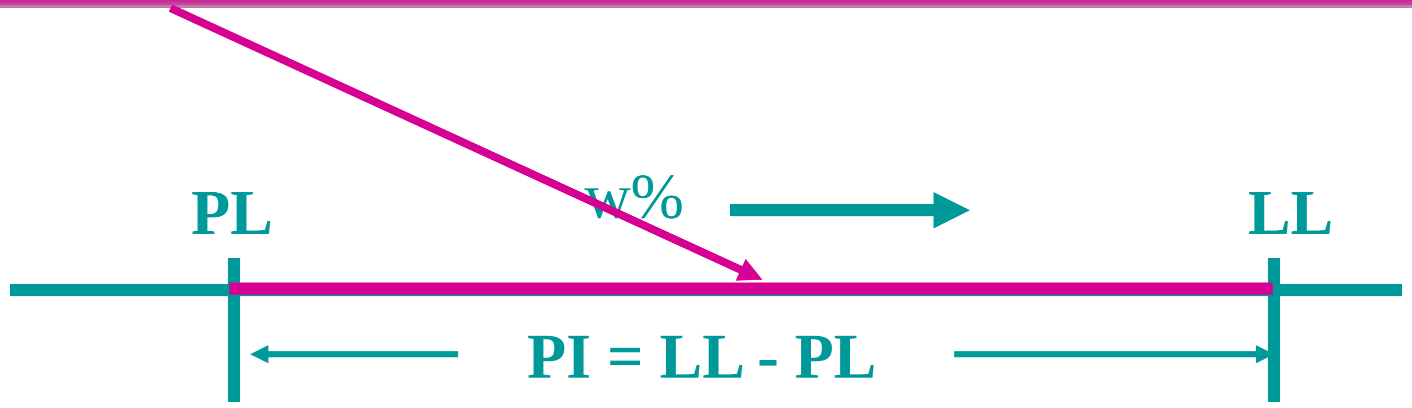


Plastic Limit (PL) at d = 20 mm

Plasticity Index

- Plasticity Index is the numerical difference between the Liquid Limit and the Plastic Limit

Plasticity Index = Liquid Limit – Plastic Limit



plastic (re-moldable)

Plasticity Index - Definition

$$PI\,(\%) = 4.12\, I_F\,(\%) \qquad I_F = \frac{w_1 - w_2}{\log\left(\frac{N_2}{N_1}\right)}$$

$$PI\,(\%) = 0.74\, I_{FC}\,(\%) \qquad I_{FC} = \frac{w_2(\%) - w_1(\%)}{\log d_2 - \log d_1}$$

Question!!

Which PI is more reasonable for construction projects? The high one or the low one?!

Plasticity and Dry Strength of Soil

Plasticity	PI(%)	Dry strength	Field test on air-dried sample
Non-plastic	0 to 3	Very low	Falls apart easily
Slightly plastic	3 to 15	Slight	Easily crushed with fingers
Medium plastic	15 to 30	Medium	Difficult to crush
Highly plastic	> 30	High	Impossible to crush with fingers

(Sowers, 1979)

- Soil with high plasticity index are called plastic soils
- A clean sand is non plastic material

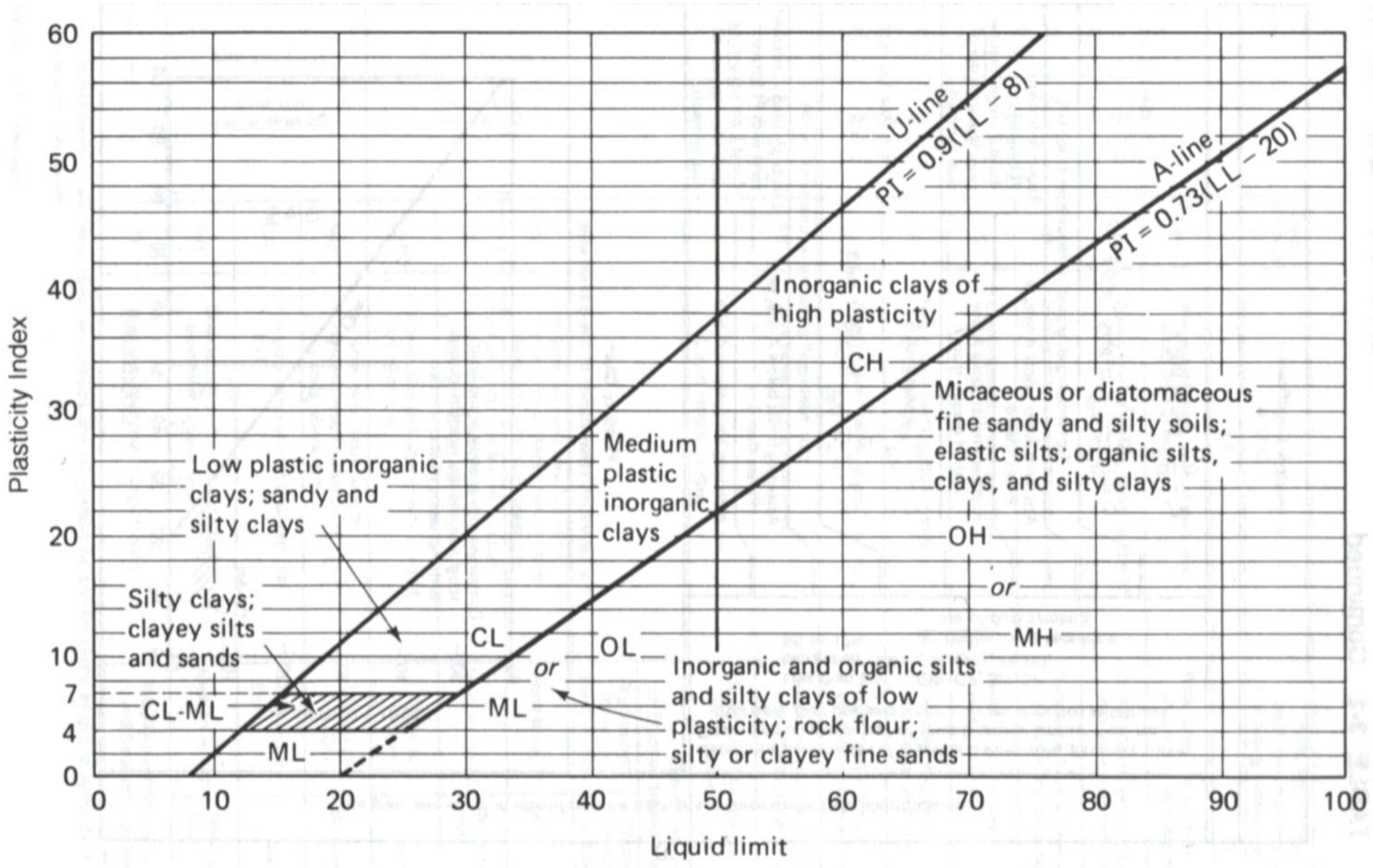
Plasticity Chart - Definition

- **Casagrande (1932) studied the relationship of the plasticity index to the liquid limit of a wide variety of natural soils.**

- **He proposed a plasticity chart**

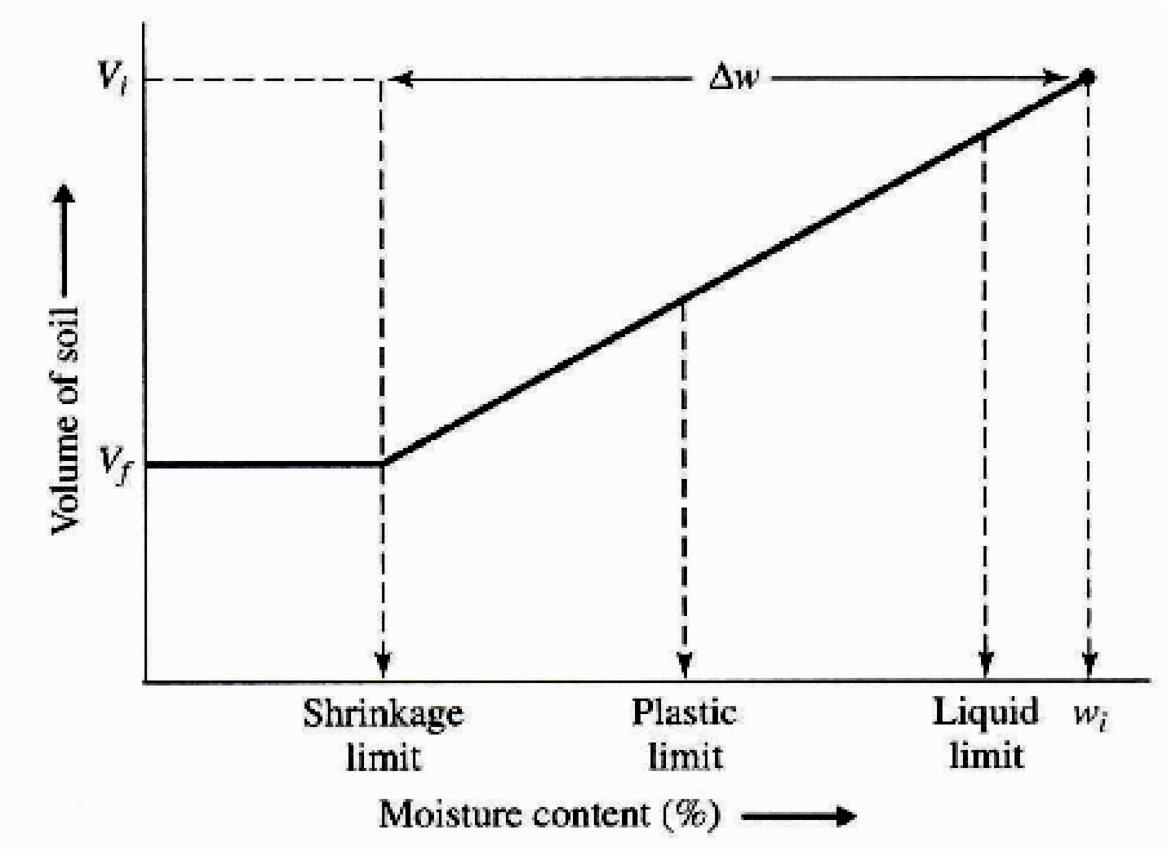
Engineering Applications

– **The Atterberg limit enable clay soils to be classified.**

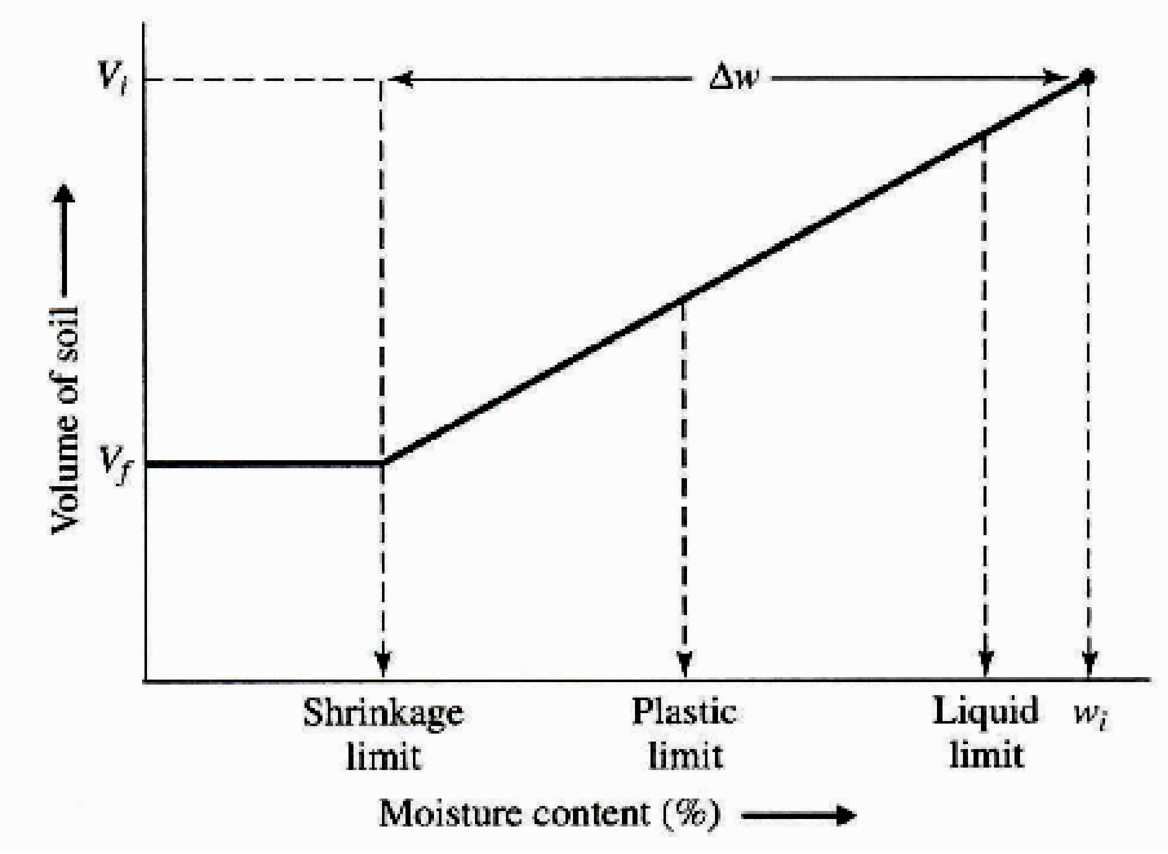


Shrinkage Limit - Definition

The moisture content, in percent, at which the volume of the soil mass ceases to change

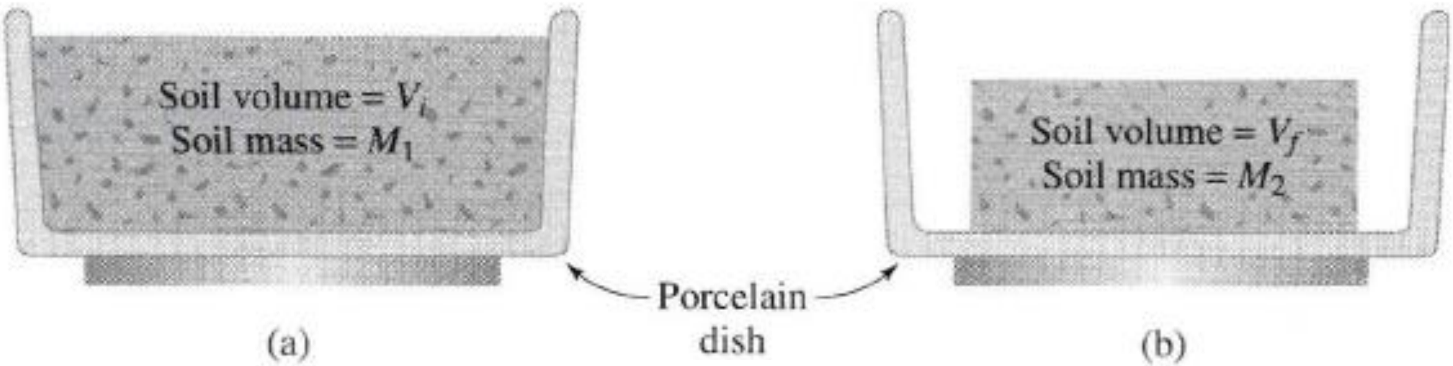


Shrinkage Limit - Definition



$$SL = w_i(\%) - \Delta w(\%)$$

Shrinkage Limit - Measurement



$$SL = w_i(\%) - \Delta w(\%)$$

$$w_i(\%) = \frac{M_1 - M_2}{M_2} \times 100$$

$$\Delta w(\%) = \frac{(V_i - V_f)\rho_w}{M_2} \times 100$$

$$w_s = \frac{\gamma_w}{\gamma_d} - \frac{1}{G}$$

$$w_s = \frac{e_{(\min \text{dry volume})}}{G}$$

Shrinkage Ratio (SR)

$$SR = \left[\frac{\dfrac{V_1 - V_2}{V_d} \times 100}{w_1 - w_2} \right]$$

Volumetric Shrinkage (VS)

$$VS = \frac{V_1 - V_d}{V_d}$$

Typical Values of Atterberg Limits

Table 10.1 Atterberg Limit Values for the Clay Minerals.

Mineral[a]	Liquid Limit (%)	Plastic Limit (%)	Shrinkage Limit
Montmorillonite	100–900	50–100	8.5–15
Nontronite	37–72	19–27	
Illite	60–120	35–60	15–17
Kaolinite	30–110	25–40	25–29
Hydrated Halloysite	50–70	47–60	
Dehydrated Halloysite	35–55	30–45	
Attapulgite	160–230	100–120	
Chlorite	44–47	36–40	
Allophane (undried)	200–250	130–140	

(Mitchell, 1993)

Indices

- **Liquidity index LI**
- For scaling the natural water content of a soil sample to the Limits.

$$LI = \frac{w - PL}{PI} = \frac{w - PL}{LL - PL}$$

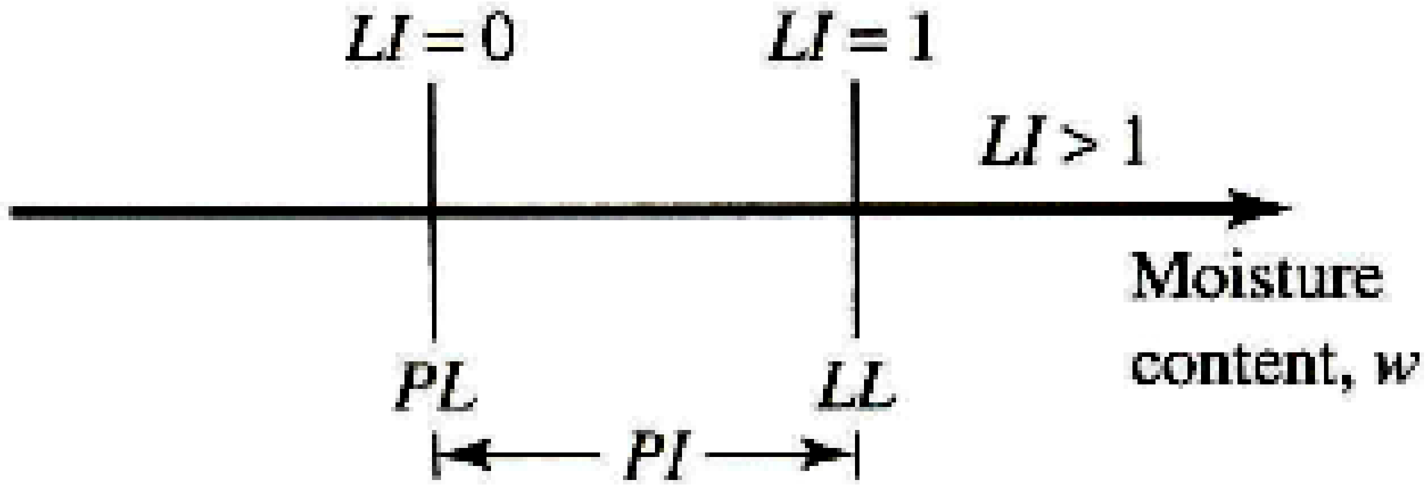
$$w \text{ is the water content}$$

LI <0 (A), brittle fracture if sheared

0<LI<1 (B), plastic solid if sheared

LI >1 (C), viscous liquid if sheared

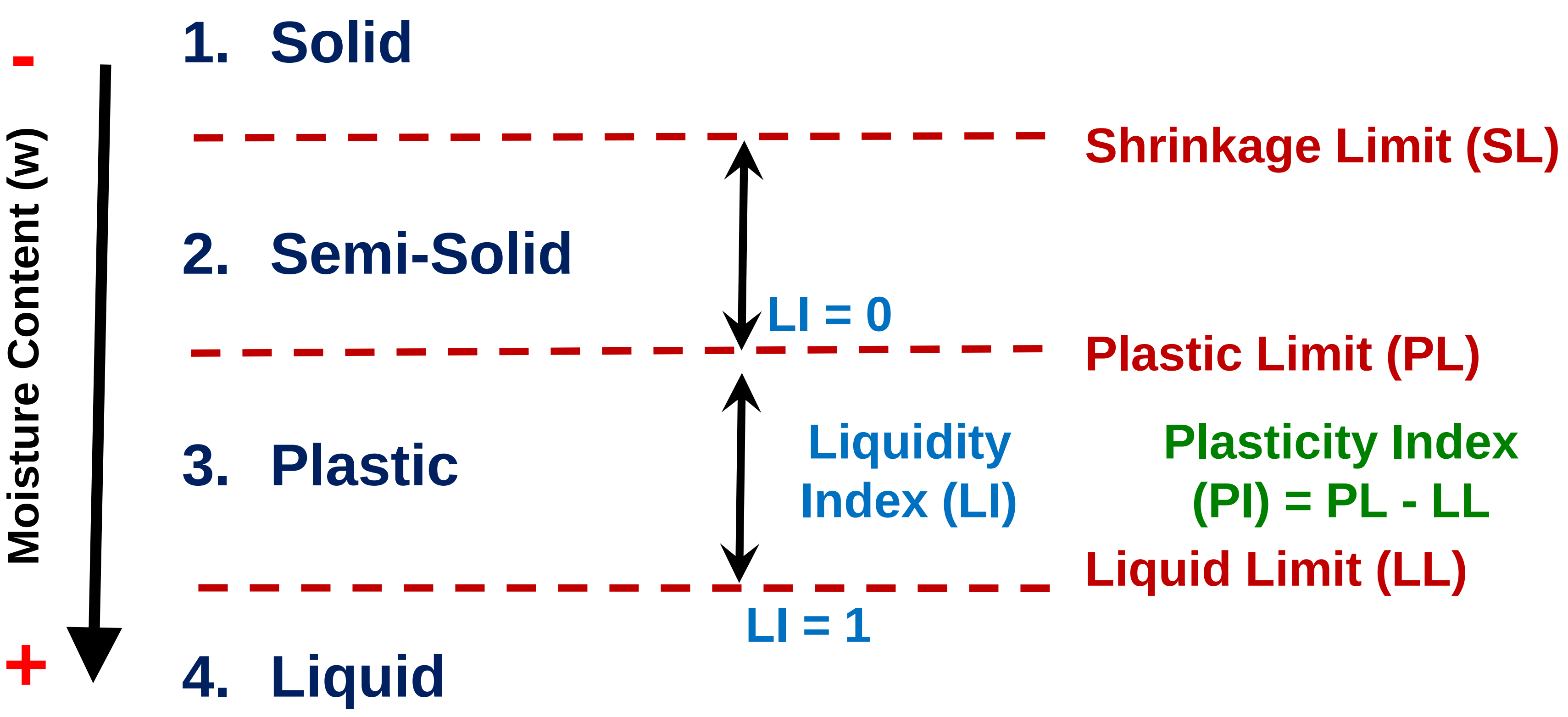
Liquidity Index - Definition



$$LI = \frac{w - PL}{LL - PL}$$

Soil Consistency - Atterberg Limits

Depending on Moisture Content soil can be divided into:

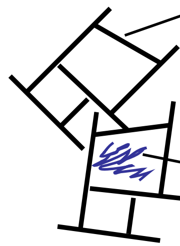


Indices (Cont.)

- **Sensitivity S_t** (for clays)

$$S_t = \frac{\text{Strength(undisturbed)}}{\text{Strength(disturbed)}}$$

Unconfined shear strength



$w > LL$

TABLE 11-7 Typical Values of Sensitivity

Condition	Range of S_t U.S.	Range of S_t Sweden
Low sensitive	2–4	< 10
Medium sensitive	4–8	10–30
Highly sensitive	8–16	> 30
Quick	16	> 50
Extra quick	—	> 100
Greased lightning	—	

(Holtz and Kavocs, 1981)

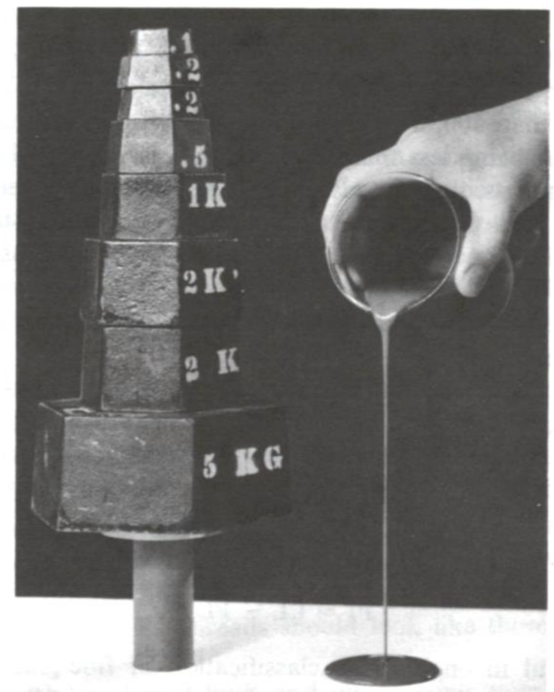


Fig. 2.9 (a) Undisturbed and (b) thoroughly remolded sample of Leda clay from Ottawa, Ontario. (Photograph courtesy of the Division of Building Research, National Research Council of Canada. Hand by D. C. MacMillan.)

Indices

- **Activity A**
- (Skempton, 1953)

$$A = \frac{PI}{\%\,\text{clay fraction(weight)}}$$

clay fraction: < 0.002mm

- **Purpose**

Both the *type* and *amount* of clay in soils will affect the Atterberg limits. This index is aimed to separate them.

- Normal clays: 0.75<A<1.25
- Inactive clays: A<0.75
- Active clays: A> 1.25
- High activity:
- large volume change when wetted
- Large shrinkage when dried
- Very reactive (chemically)

Mitchell, 1993

Table 10.4 Activities of Various Clay Minerals.

Mineral	Activity[a]
Smectites	1–7
Illite	0.5–1
Kaolinite	0.5
Halloysite ($2H_2O$)	0.5
Halloysite ($4H_2O$)	0.1
Attapulgite	0.5–1.2
Allophane	0.5–1.2

4.6 Indices (Cont.)

- **Activity A**
- (Skempton, 1953)

$$A = \frac{PI}{\%\,\text{clay fraction}(\text{weight})}$$

clay fraction: < 0.002mm

•**Purpose**

Both the *type* and *amount* of clay in soils will affect the Atterberg limits. This index is aimed to separate them.

•Normal clays: 0.75<A<1.25

•Inactive clays: A<0.75

•Active clays: A> 1.25

•High activity:

•large volume change when wetted

•Large shrinkage when dried

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Mitchell, 1993

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